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THE SPECTROSCOPIC DETERMINATION OF AQUEOUS VAPOR[1]

By F. E. FOWLE

The purpose of this research is to make possible the determination of the amount of aqueous vapor present in the atmosphere by the observation of the absorption at certain wave-lengths produced by this vapor in the spectra of bodies observed through it. This requires the noting in the laboratory of the absorption resulting at these wave-lengths from known amounts of water vapor at as nearly as possible the same conditions as to pressure, density, and temperature that exist in the atmosphere.

ABSORPTION BANDS

The water-vapor bands in the infra-red spectrum known as Φ ($\lambda = 1.13\,\mu$) and Ψ' ($\lambda = 1.47\,\mu$) have been chosen for this purpose. Fig. 1*a* shows the bottom of Φ, Fig. 2*a*, Ψ with Ψ' as these bands appear in the solar energy-spectrum. Fig. 3 shows these same bands as well as Ω and the band at about $2.25\,\mu$, also due to water vapor, as they appear in the energy-spectrum of a Nernst glower when observed through vapor corresponding to 0.101 cm precipitable water.[2] The form of these bands depends not only on the

[1] Published by permission of the Secretary of the Smithsonian Institution.

[2] In this discussion the amount of absorbing vapor will be stated, for brevity, as so much precipitable water, meaning the depth of water which, if evaporated into a column of the same section, would produce the absorbing layer of vapor. This should not be construed as meaning that the liquid water produces the same amount of absorption as the corresponding vapor.

amount of aqueous vapor absorption but also on the purity of the spectrum as influenced by the widths of the slit and of the bolometer and the character of the spectroscope. A line has been drawn

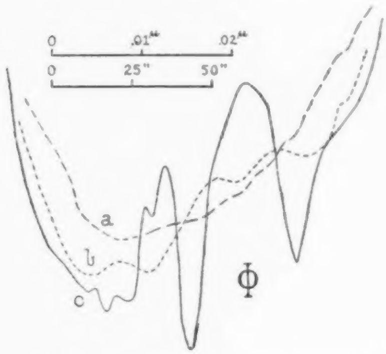

FIG. 1.—Energy-curves of bottom of water-vapor band Φ.

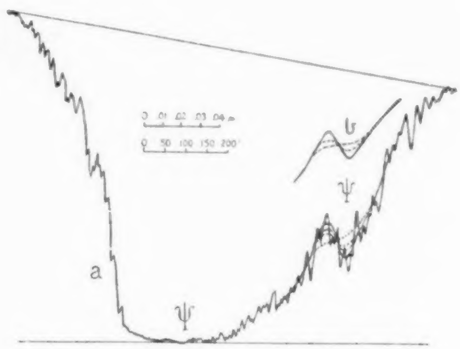

FIG. 2.—Energy-curves of Ψ with Ψ'

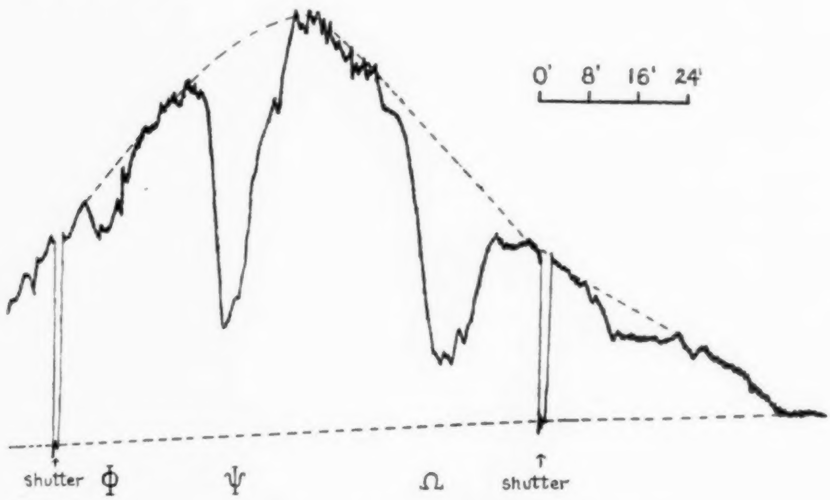

FIG. 3.—Energy-spectrum through water vapor of Nernst glower

over the tops of the large bands as indicated in Figs. 2 and 3, and the transmissibility of radiation taken as the ratio of the ordinates of the energy-curve at the chosen places to the ordinates of this line directly above. Since slight absorption due to aqueous vapor

may exist in the spectrum on either side of the bands Φ and Ψ, this ratio may not give exactly the true transmissibility. But the error, if any, should affect the laboratory work and its applications in the same sense and, therefore, should be almost wholly eliminated in the applications of this method.

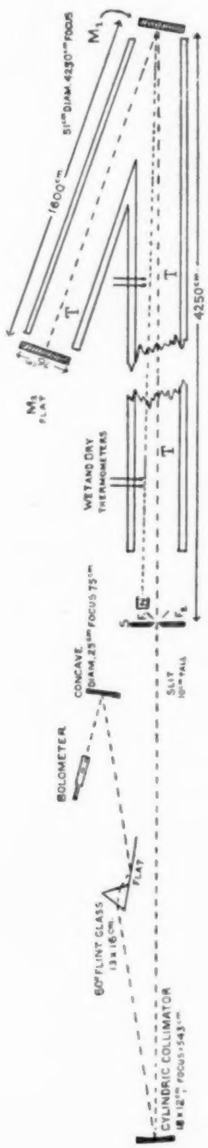

FIG. 4.—Plan of apparatus

APPARATUS AND METHOD OF OBSERVING

Light from the source *N*, composed of Nernst lamps, passed through the tube *T*, containing water vapor, to the concave mirror M_1, 51 cm in diameter and 42.7 meters focus, thence, collimated, to the flat mirror M_2, 76 cm in diameter, back to M_1, and then to focus on the slit of the spectroscope at *S*. Sometimes, before entering the spectroscope, the beam was returned over the course through the water vapor by the two flats F_1 F_2 beside the slit. The first arrangement gave a path through the water vapor in the tube of about 117 meters, to which must be added the path through the spectroscope, giving a total path of 128.5 meters; the corresponding value for the second case was 245.5 meters (806 feet). This long path greatly reduced the intensity of the lamp's image at the slit of the spectroscope. There also resulted a serious vibration of this image due to the consequent magnification of the small tremors of the mirrors. These two causes went far to limit the accuracy attainable in the observations.

The lamp used as a source of radiation was composed of two layers of Nernst alternating-current, 110-volt

lamps, four glowers wide, five long. The rear layer was so adjusted as to shine through the interstices of the front layer, presenting a glowing surface about 90 by 5 mm. These glowers were placed in the rear of a rectangular cavity, 100 by 10 mm, and 40 mm deep, cut into a block of soapstone.

The spectroscope was supplied with a 60° prism of flint glass described in the first volume of the *Annals* of this Observatory, p. 45. The bolometer was 0.1 mm wide, 12 mm tall, and subtended 27″ (about 0.006 μ in the region of the spectrum under study). The slit was from 0.5 to 2 mm in width by 100 mm in height, subtending from 20″ to 78″. The other details of the spectroscope may be learned from Fig. 4. The galvanometer had a time of single swing of about 3 seconds. Its indications were recorded on a moving photographic plate as described in the above *Annals*, p. 58.

The large galvanized-iron tube for the water vapor was open at its ends, double-walled, and covered with a canvas tent to protect it from rapid temperature changes. A rotary blower served to stir the vapor within the tube and free it from stratification just before an observation. It was not feasible to run the blower during an observation because of the tremors communicated to the mirrors and to the galvanometer. Steam could be forced in by the blower to increase the amount of aqueous vapor, but most of the measures were taken with the amount of vapor normally present in the tube. All the measures were at atmospheric pressure.

MEASUREMENT OF THE QUANTITY OF AQUEOUS VAPOR

The amount of aqueous vapor was determined by wet and dry thermometers at the spectroscope, at the mirror shelters and at several places in the tube. These were read while the air was stirred by the fan. Check determinations were made several times by Mr. L. B. Aldrich, who absorbed in tubes of calcium chloride and phosphorus pentoxide the water vapor from known volumes of air taken from the tube. The following table gives the water per cubic meter as measured by the two methods:

By Wet and Dry Thermometers	Absorbed by $CaCl_2$ and P_2O_5
3.25 grams per cu. m	3.29 grams per cu. m
3.82 " " "	3.85 " " "
7.96 " " "	8.76 " " "

The following shows a determination of the amount of water vapor in the large tube just preceding and just after an observation on the transmissibility of radiation through the water vapor:

August 11, 1911: Barometer 762 mm					
Dry: Wet:	34°6 26.1	37°4 27.5	36°45 26.8	35°65 C. 26.6	$11^h\ 45^m$
Grams per cu. m before observation..............	19.5	20.7	19.8	19.8	Mean 20.0
Dry: Wet:	35°8 26.55	38°85 27.75	38°1 27.45	37°15 C. 26.85	$12^h\ 30^m$
Grams per cu. m after observation.............	19.7	20.3	20.6	19.5	Mean 20.0

CORRECTIONS FOR THE WIDTHS OF THE SLIT AND BOLOMETER

Perhaps the greatest obstacle to the use of the spectroscope for the quantitative determination of vapor producing an absorption line or band lies in the allowance for the purity of the spectrum. The greater the purity, the greater generally is the observed absorption at the bottom of a band. With the spectroscope used here the resolving power, as dependent upon the optical system, is such that in the region of the spectrum studied, two lines separated by about 3″ (0.0007 μ, 60° flint-glass prism) may be resolved. The bolometer subtends an angle of 27″ (0.0046 μ at Φ, 0.0062 μ at Ψ); at the same places in the spectrum, the slit, from 20″ to 78″ (0.0034 μ to 0.0134 μ at Φ, 0.0046 to 0.0179 at Ψ). The limiting angle of resolution of the prism, 3″, is therefore negligible in the following discussion compared with the sum of the angles subtended in the spectrum by the slit and bolometer, 47″ to 105″. In the spectroscope used for solar-constant observations at Mount Wilson the bolometer-plus-the-slit subtended about 92″ (0.022 μ at both Φ and Ψ, 60° ultra-violet glass prism).

In spectro-bolometric researches energy-curves are obtained with a bolometer and slit of finite widths and an attempt is generally made to correct the form of the observed curves to represent the distribution of energy which would have been obtained had the bolometer and slit been indefinitely narrow. Professor Runge has published a method for obtaining such corrections.[1] Although

[1] *Zeitschrift für Mathematik und Physik*, **42**, 205, 1897.

some improvement in the observations is thus made, evidently no mathematical process can replace high purity for revealing spectrum details. Fortunately in the present research a more satisfactory expedient is available. It is desired to reduce the observations made with the water vapor in the tube, not to a grade of purity corresponding to zero slit and bolometer, but to a grade of purity corresponding to that of some other spectroscope. This Observatory has published[1] the form of the bands Φ and Ψ (Figs. 1 and 2 of this article) as determined with apparatus far better as regards purity than the apparatus in use for the present research. By measuring areas included under those old curves between ordinates separated by any chosen spectrum intervals, the ordinates which would have been observed with a spectroscope in which the slit and bolometer combined would cover the corresponding spectrum interval could be determined. In this way the old curves with high purity have been transformed to the conditions of the apparatus prevailing during the tube work at Washington or during the solar-constant work at Mount Wilson. From the results of such transformations it is possible to reduce the measures of the present research and of the Mount Wilson work to any desired condition of purity short of those which prevailed in the old work published in Vol. I of the *Annals.*

Curves computed for various degrees of purity as just described are indicated by the dotted lines in Figs. 1 and 2. For instance, in curve *b*, Fig. 1, the slit plus the bolometer covered a region in the spectrum of 0.013 μ, curve *c*, 0.025 μ. It is interesting to note the peculiar positions of the minima in curve *b* as compared with those of curve *a*.

These corrections for the finite widths of the slit and bolometer are a function of the amount of absorption as well of the purity of the spectrum. To determine this second effect, a new curve (*b*, Fig. 2) was determined from curve *a* of the same figure using the formula[2] $d_w = d_0 a^w$, where d_w is the deflection observed through an amount of water vapor w; d_0 that with no vapor, and a the transmissibility with unit thickness of vapor. For the computed curve w was taken as equal to $\frac{1}{3}\,w$ of the observed curve. By such means

[1] *Annals*, Vol. I, Plates XX, XXI A and B.

[2] *Smithsonian Miscellaneous Collections*, **47**, 1, 1904.

a series of corrections was obtained as known functions of the purity and of the observed coefficients of transmission.

OBSERVATIONS

The accompanying table contains the observations on the transmissibility through water vapor of the radiations of the wavelengths 1.13 (Φ) and 1.47 μ (Ψ′).

Date	Barometer	Temperature of Vapor	Slit-Width	Log. of Transmission Observed*		Corrected†		Water‡ Vapor	Observations
	mm	C	mm	1.13μ	1.47μ	1.13μ	1.47μ	cm	
Sept. 2, '09..	764	24°	(1)	0.977	0.984	0.979	0.985	0.013	......
Aug. 24, '09..	766	29	.....	......	.983	......	.983	.015	......
Aug. 21, '11..	767	29	0.5	......	.966?	......	.970?	.016	......
Aug. 25, '09..	...	31	1.0	.974	.970	.977	.972	.020	......
Sept. 2, '09..	764	28	(1)	.905	.910	.914	.917	.101	2, 2
May 13, '11..	765	32	2.0	.897	......	.903	......	.128	......
Aug. 21, '11..	767	32	0.5	.876	.923?	.891	.931?	.132	1, 2
Aug. 20, '09..	757	35	.....	......	.913?	......	.913?	.165	......
Aug. 24, '09..	766	33	.....	......	.895	......	.895	.171	......
Aug. 25, '09..	...	35	1.0	.855	.875	.869	.884	.192	2, 2
Aug. 9, '11..	762	36	2.0	......	.901	......	.899	.209	......
Aug. 10, '11..	764	36	1.0	.855	.853	.866§	.873§	.210	3, 3
	...	..	0.5	.828	.870	......	......	......	......
	...	..	0.5	.854	.857	......	......	......	......
Aug. 24, '11..	764	35	1.0	.806	.862	.852	.871	.233	2, 2
	...	..	0.5	.869	......	......	......	......	......
May 13, '11..	765	38	2.0	.848	.896	.857	.894	.244	......
Aug. 19, '11..	761	29	1.0	.808	.838	.825	.849	.249	......
Aug. 21, '11..	767	30	1.0	.799	.820	.837§	.851§	.259	4, 4
	...	29	1.0	.834	.885	......	......	......	......
	...	31	1.0	.807	.826	......	......	......	......
	...	31	0.5	.824	.834	......	......	......	......
Aug. 11, '11..	762	38	1.0	.797	.852	.824§	.849§	.262	3, 3
	...	38	0.5	.804	.805	......	......	......	......
	...	40	0.5	.807	.866	......	......	......	......
May 12, '11..	761	35	2.0	.840	.866	.849	.863	.275	......
July 29, '11..	765	32	2.0	.826	.825	.836	.822	.369	2, 2
Aug. 19, '11..	761	27	1.0	.781	.838	.800	.848	.370	3, 3
Aug. 10, '11..	764	38	1.0	.699	.774	.810§	.807	.392	3, 3
	...	38	1.5	.840	.795	......	......	......	......
	...	38	2.0	.800	.840	......	......	......	......
	...	34	2.0	.784	.793	.795	.789	.398	......
Aug. 24, '11..	766	32	1.0	.779	.811	.798	.824	.422	3, 3
May 19, '11..	760	33	2.0	.778	.839	.789	.836	.438	......
Aug. 11, '11..	762	35	1.5	.755	.774	.772	.791	.492	2, 2
	...	36	1.0	.740	.787	......	......	......	......
	...	39	1.5	.730	.784	.748	.791	.540	......

* Logarithm of the percentage radiation transmitted, as observed with the slit indicated in the table.

† Same corrected to the spectroscope in use at Mount Wilson for solar-constant determinations; slit + bolometer covers 0.022 μ in the spectrum at 1.13 and 1.47 μ.

‡ Depth of water layer which, if evaporated into column of the same section, would produce the amount of absorbing vapor.

§ Weighted mean.

Figs. 5 and 6 give graphical representations of these results for Φ and Ψ' reduced to spectroscopic conditions where the slit plus the bolometer covers a region $0.022\ \mu$ in the spectrum. These are approximately the conditions fulfilled by the spectroscope in use at Mount Wilson during 1910 for solar-constant determinations.

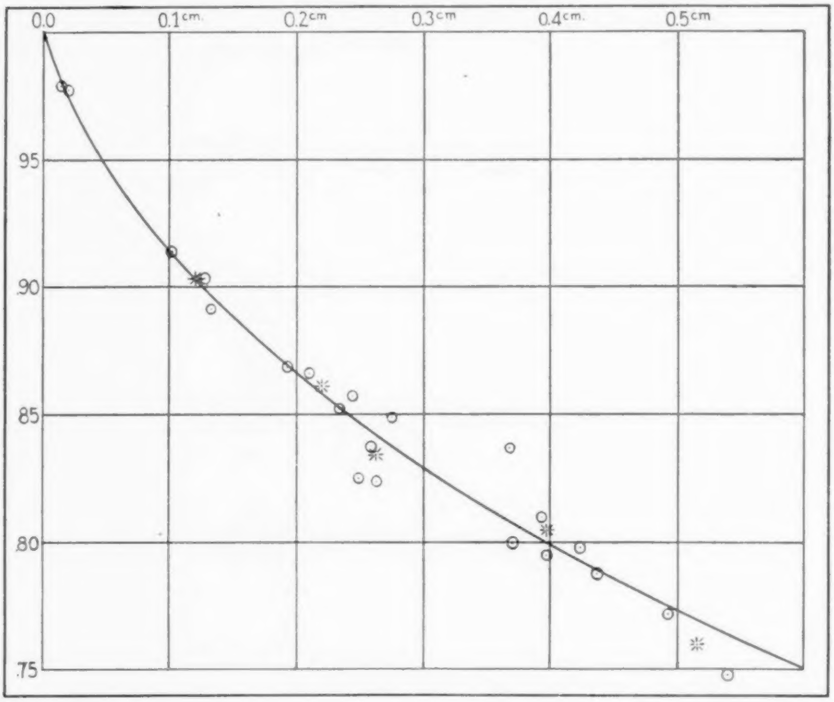

FIG. 5.—Abscissae, precipitable water; ordinates, logarithm of transmissibility of radiation at Φ $(1.13\ \mu)$.

The ordinates are the logarithms of the percentage transmissibility of radiation at $1.13\ \mu$ and $1.47\ \mu$, respectively, the abscissae, the corresponding quantities in centimeters of precipitable water. Besides the separate observations there are indicated on the plot by stars the mean results of all the determinations reduced by groups.

EXTENSIONS OF THE RESULTS FOR GREATER AMOUNTS OF WATER VAPOR

The tube experiments just described extend over a range of precipitable water up to 0.5 cm. According to Humphreys[1] the precipitable water in the path of a beam from the zenith to sea-

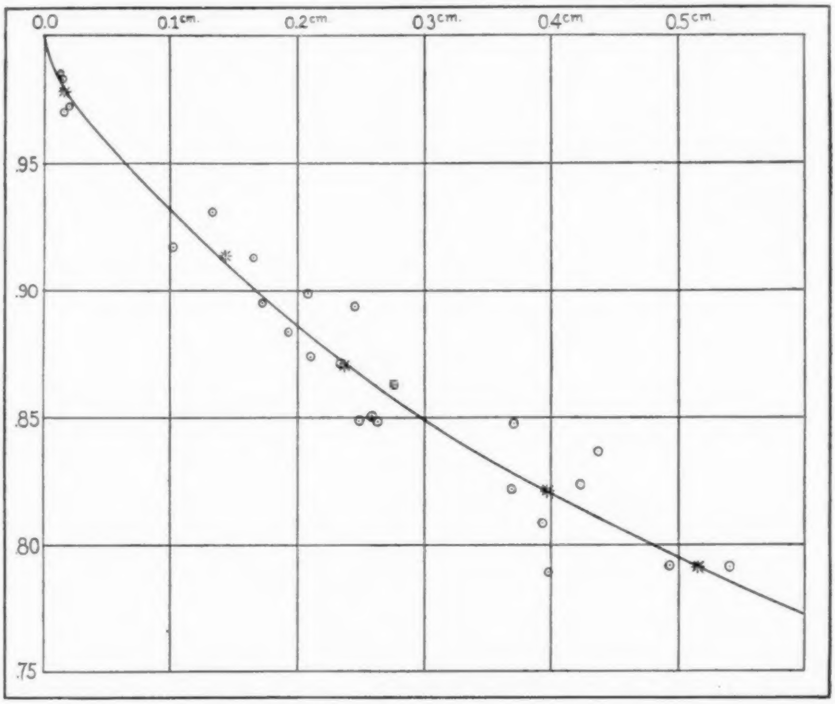

FIG. 6.—Abscissae, precipitable water; ordinates, logarithm of transmissibility of radiation at Ψ^1 (1.47 μ).

level may often reach 1.5 cm. It was not feasible to extend the tube experiments directly to such quantities; but from the Mount Wilson bolographs taken at high and low sun the curves of Figs. 5 and 6 may be extended, provided days may be found when the aqueous vapor in the air remained nearly constant for two or three

[1] *Bulletin of the Mount Weather Observatory*, **4**, 121, 1911.

hours. For the relative lengths of the paths passed through by the radiation from the sun may be computed, being proportional to the secant of the zenith distance of the sun; then if the absolute amounts of the water vapor traversed during the high-sun observations are found by means of Fig. 5 or 6, the corresponding amounts of vapor in the path of the lower-sun observations may be determined.[1] If the earlier portion of the line determined by means of these solar observations coincides with the line from the tube work we may feel considerable certainty that the portion beyond furnishes a reasonable extrapolation. Having extended the curve one step, the new portion may be used likewise for still further extension. It is worth noting that on the days chosen by the criterion that the earlier portion of the plotted observations should agree in curvature with the tube work, the readings of the wet and dry thermometers at the top of the mountain indicated a greater constancy of vapor-pressure than usual.

As a result of such extensions Fig. 7 was obtained. The full curve represents the data for Ψ', the dotted line, for Φ. The ordinates are the logarithms of the percentage transmission of radiation at Φ and Ψ', respectively, the abscissae, the corresponding precipitable water. There are also given on this diagram the corrections necessary to reduce the curve for Ψ to various other spectroscopic conditions, namely: where the slit plus the bolometer covers 0.025, 0.020, 0.015, and 0.010 μ in the spectrum. On this subsidiary plot the abscissae correspond to the ordinates of the

[1] For example, the following data on the transmission at Ψ were obtained from observations at Mount Wilson:

Secant zenith distance	1.00	1.50	2.00	3.00	3.50
Logarithm transmission	0.824	0.783	0.740	0.670	0.636

The first two of these transmissions lie within the range of Fig. 6 and give for the corresponding amounts of vapor: 0.386 cm precipitable water and 0.547 cm. The latter figure is for a path 1.50 times as long as for the first and reduced to the same path, gives 0.365; the mean of 0.386 and 0.365 is 0.375; multiplying this mean by the relative paths as given in line one of this note we have for extending the curve:

Amount precipitable vapor	0.375	0.562	0.750	1.125	1.312 cm
Logarithm transmission	0.824	0.783	0.740	0.670	0.636

larger plot (log. transmission), the ordinates, the amount by which the curve must be lowered (raised for 0.025 μ). In other words, the ordinates are the logarithmic percentage corrections plotted on the same scale as used for the logarithms of principal line.

The laboratory observations on the transmissibility at Φ and Ψ', as given in columns 5 and 6 of the table, probably have nearly equal weight. When they are reduced to the conditions of the Mount Wilson spectroscope the figures for the latter have considerably the greater weight. At Ψ' the spectroscopic conditions in the laboratory and at Mount Wilson were nearly identical as to purity, and the correction was therefore small. For Φ, however, since the dispersion in this region is considerably smaller in the Mount Wilson spectroscope, the corresponding correction is much larger and, because of the shape of the band, is more doubtful.

VARIATION OF THE ABSORPTION WITH PRESSURE

It may be objected that the laboratory work has all been done at atmospheric pressure while some of the vapor of the atmosphere is under somewhat reduced pressures. Unfortunately the variation of the transmission with the pressure has not been determined for the bands employed here. But Miss Eva von Bahr[1] gives for the water-vapor band at 2.7 μ the following values for the absorption of a constant amount of aqueous vapor under varying pressures:

105 mm	4.6 per cent	405 mm	8.5 per cent
235	7.2	570	10.6
370	8.6	755	12.0

The increase in pressure was produced by dry air which exercises practically no absorption at this place. Miss von Bahr found that the absorption due to a vapor depended to a great degree upon the total pressure exerted upon it, not upon its own partial pressure. She also states that the "absorption as dependent upon the total pressure is in general, for the same gas, the same in the different bands."

[1] *Ueber die Einwirkung des Druckes auf die Absorption ultraroter Strahlung durch Gase*, p. 68, Upsala, 1908.

It may therefore give a fair estimate of the magnitude of this pressure effect in the region of Φ and Ψ′ to use these observations made at 2.7 μ. Using the distribution of aqueous vapor at different altitudes as given by Humphreys (*op. cit.*), a vertical column of air which would give a transmission of 88 per cent, with the pressure uniform throughout at 760 mm, would give, with a distribution of pressures such as actually exists in the atmosphere, according to the measures of Miss von Bahr, 90 per cent in summer, 89 in winter. With the distribution of vapor above Mount Wilson, the transmission comes out 90 per cent for both summer and winter. This computation indicates that it would take a slightly greater amount of vapor to produce an absorption noted in the spectrum of a celestial body than the curves of Fig. 7 would show. If the observations are made at the surface of the earth, the difference would be 1 or 2 per cent and about 3 per cent if made at Mount Wilson.

Before concluding the writer wishes to express his gratitude to Mr. Abbot for his criticisms and suggestions while preparing this matter for publication.

SUMMARY

By laboratory experiments on the transmissibility of radiation through long columns of air containing known amounts of water vapor the dependence of transmission on the water-vapor content has been determined for the infra-red bands Φ and Ψ′. The direct determinations cover quantities of water vapor up to a depth of 0.5 centimeters of precipitable water. Beyond this the determinations have been extended by aid of solar observations made on Mount Wilson. This extension does not require assumptions as to the actual quantities of water vapor in the solar beam, but only as to the relative quantities as fixed by the length of path of the beam. As the purity of the spectrum enters into the results it has been necessary to determine the dependence of transmission on water vapor for different values of combined slit- and bolometer-width. While the experiments have been made only at atmospheric pressure, a computation is given which shows that the results are probably applicable with slight correction to the actual

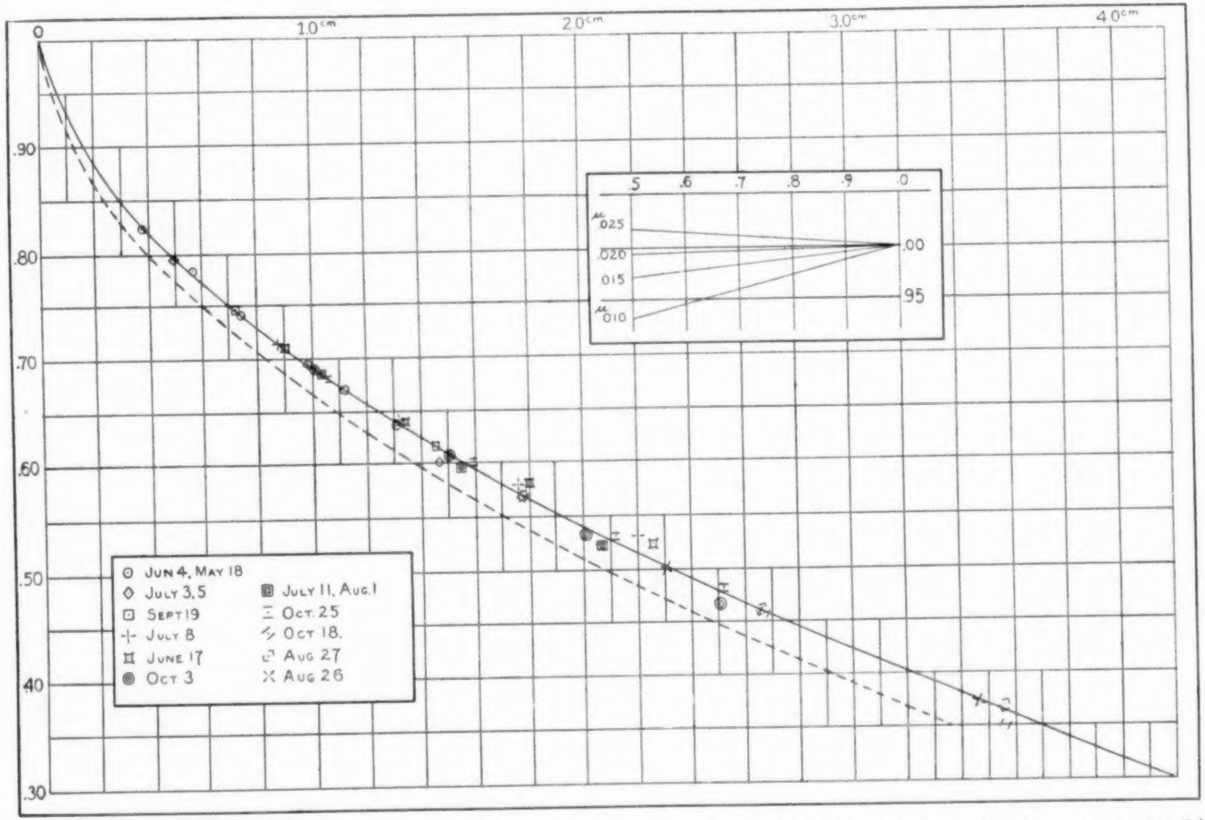

FIG. 7.—Abscissae: precipitable water. Ordinates: log. percentage transmissibility for radiation. Continuous curve for Ψ'; dotted curve for Φ.

Subsidiary plot: abscissae, log. percentage transmission at Ψ'; ordinates, log. percentage correction to Ψ' curve for slit + bolometer $= 0.010\,\mu$, $0.015\,\mu$, $0.020\,\mu$, and $0.025\,\mu$.

pressures at which water vapor occurs in the atmosphere. Accordingly, a method has been established by means of which the total quantity of water vapor between the observer and the sun may be easily determined by spectro-bolometric observations. It is proposed in subsequent papers to give applications of the method.

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THE THREE-PRISM STELLAR SPECTROGRAPH OF THE MOUNT WILSON SOLAR OBSERVATORY[1]

By WALTER S. ADAMS

The original design of the 60-inch reflector provided for the use of three stellar spectrographs in connection with the three principal mirror combinations. The first of these to be completed was the powerful spectrograph of 5.5 m focal length used with the coudé combination of telescope mirrors at the equivalent focus of 45.7 m. This instrument was employed for the investigation of the spectra of some of the brighter stars under high dispersion.[2] In the following year a small low-dispersion spectrograph was constructed for use at the primary focus of the large mirror. On account of the presence of the Newtonian plane mirror it was necessary to mount this spectrograph on the side of the tube of the telescope and to introduce an auxiliary reflection between the slit and the collimating lens. The instrument proved extremely efficient for qualitative work upon the spectra of faint stars, and the radial velocity results obtained with it were so promising as to warrant the construction of an instrument of similar type mounted directly in the axis of the telescope. In this way the loss of light at two reflecting surfaces is avoided and much greater mechanical stability is insured. This spectrograph is now nearing completion in the Observatory instrument shops.

Intermediate between these two spectrographs, one of very high and the other of low dispersion, is the three-prism spectrograph mounted at the lower end of the telescope tube and employed with the Cassegrain combination of mirrors. At this point the equivalent focal length of the telescope is 24.4 m, or the ratio of aperture to focal length is 1 to 16. This is much the same ratio as that of most of the large refracting telescopes used for spectrographic work, and accordingly the dimensions of the optical system in the

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 59.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 50; *Astrophysical Journal*, **33**, 64–71, 1911.

spectrograph are similar to those of some of the larger stellar spectrographs employed in radial velocity determinations. The instrument was built by William Gaertner & Co. of Chicago in accordance with designs provided by the observatory, and has been in regular use on Mount Wilson during the past year.

The very massive character of the telescope mounting and the proximity of the spectrograph to the center of rotation of the telescope made the consideration of its weight of less importance than is usually the case. Accordingly the main frame of the instrument consists of a single heavily ribbed iron casting. The base of the casting is rectangular in shape and about 84×61 cm in size. It is accurately surfaced and is attached directly to a planed flange upon the frame of the telescope by means of a number of strong studs. The slit of the spectrograph is behind the face of the casting and so is well protected from possible injury during the process of changing of instruments. The opening in the telescope frame through which the light passes from the diagonal plane mirror is about 33 cm in diameter, being made sufficiently large to provide for direct photography at this point. The corresponding aperture in the spectrograph casting opposite the slit is about 15 cm square.

At right angles to this base and forming a part of the same casting is the large plate which constitutes the frame of the spectrograph. It is about three-quarters of an inch in thickness and is planed over a large portion of its surface. Fastened directly to this plate are the prisms and the tubes carrying the collimating and camera lenses. The plate is about 140 cm long and tapers slightly from its base toward the prism box.

The focal length of the collimating lens was determined by two considerations: first, the size of the prisms available for use; and second, in a less degree, by the fact that a very long instrument would prevent observations of the region of the sky near the pole on account of striking the floor of the dome. The difficulty of securing optical glass of a quality suitable for prisms of considerable size is very great at the present time, as is fully recognized by most spectroscopists. Fortunately, in the case of this spectrograph, prisms of good quality were known to be available. At the time

at which the five-foot spectroheliograph was designed four prisms 210 mm high and with faces 125 mm wide were ordered from Jena. Three of these proved to be of excellent quality. They are of glass No. O. 102, with an angle of 63° 29′, which provides for a deviation of 180° at $H\gamma$ when three prisms are employed. Since only two prisms are required for the work of the spectroheliograph the third prism became available for the stellar spectrograph. Accordingly it was cut in our optical shop into three prisms, each 67 mm high and with faces the same, of course, as those of the original prism; that is, 125 mm in width. A prism with faces of this size would utilize a beam 59 mm in width at minimum deviation for $H\gamma$. In view of these considerations a diameter of 64 mm (2.5 inches) was fixed upon for the aperture of the collimating lens, which with a ratio of 1 to 16 gives a focal length of 102 cm (40 inches). When more than one prism is employed there is an appreciable loss of light for wave-lengths other than that at minimum deviation on account of the spread of the beam, but as the spectrograph was designed largely for work with one prism it seemed desirable to retain the large aperture. The collimating lens is a cemented triplet corrected for the $H\gamma$ region, made by the J. A. Brashear Co., and has proved very satisfactory in use.

Two camera lenses have been employed with the spectrograph. The longer one of these is an uncemented triplet by Brashear of 88 mm aperture and 102 cm focal length. The other is a Cooke lens of the "Astro-photographic" type with an aperture of 102 mm and a focal length of 46 cm. Both lenses give excellent definition, and the latter, on account of the transparency and the thinness of its components, has proved exceptionally efficient photographically. For all work with a single prism the longer camera has been used, while with two prisms the shorter camera has usually been found sufficient.

An important advantage possessed by the form of construction adopted in the spectrograph is that of adaptability for different regions of the spectrum. The prisms are mounted in cast-iron cells which rest upon three legs. These pass through slotted openings in the main plate of the spectrograph and are clamped rigidly with nuts upon the other side of the plate. The slotted

openings are provided with scales and the prism mounting has upon it an index by which they may be read. The scale-readings for each prism were determined when the three prisms were originally adjusted for minimum deviation at a definite wave-length, and in case it is desired to set the prisms for any other wave-length, changes are made in the scale-readings corresponding to the difference of deviation. Similarly the camera is mounted on a heavy iron plate which swings through an angle corresponding to that of the third prism, and is clamped in position by powerful bolts. This simple arrangement has proved most satisfactory in use.

The great length of the camera regularly employed with the single-prism arrangement and the difficulty of supporting it with sufficient rigidity led to the interposition of a mirror between the prism and the camera lens. In this way the camera may be left in the same position as that used when three prisms are employed. The objections to this proceeding are: first, the loss of light by reflection at the mirror; and, second, the difficulty of supporting the mirror with sufficient stability. The first objection is not very serious, since the mirror is entirely inclosed, and the silver coat deteriorates very slowly and may be kept in excellent condition. Under these conditions the reflecting power for the region of the spectrum usually photographed is not far from 90 per cent. The second objection is met by making the mirror exceptionally thick and holding it in a strong cell in much the same way as a diffraction grating is supported. The photographs obtained with the spectrograph have shown no impairment as regards definition or accuracy of results since the mirror was employed. When two prisms are used the mirror cell is moved toward the camera lens along a slide provided with a graduated scale and is clamped in position.

For comparison spectrum purposes the iron arc is used. The arc lamp is fastened to the outside of the spectrograph case. The light passes through a mica window and falls upon a lens which renders it roughly parallel. This throws it upon a piece of opal glass which thoroughly diffuses it, and an image of this glass is thrown upon the slit by a second lens. The glass, accordingly, serves as the effective source of illumination for the spectrograph. A totally reflecting prism, which is moved in front of the slit by a

handle on the outside of the spectrograph, serves to reflect the light into the instrument. An occulting screen with small openings through which the light from the star or from the arc may fall upon the slit also is controlled by a rod projecting from the side of the spectrograph.

The entire spectrograph is inclosed in a wooden case, the walls around the prism-box being of double construction. For purposes of automatic temperature control the convenient device first employed by Professor Campbell has been adopted, a pair of Draper thermostat strips with platinum contacts acting through a relay to throw the heating current on and off. The heating coils are placed outside of the first wall of the prism-box and are distributed as symmetrically as possible about it. A small fan placed inside of the outer cover serves to distribute the air around the outside of the prism-box and prevents stratification. When the instrument is under temperature control, readings of a thermometer placed inside the prism-box indicate ranges of temperature rarely greater than $0^\circ.1$ to $0^\circ.2$ C. throughout an entire night.

For guiding purposes we have used the customary device of a reflecting slit, the jaws being inclined at an angle of about $2^\circ.5$ to the normal. The reflected light is first collimated by a small lens and then reflected by diagonal prisms through a long tube to a point beneath the spectrograph where it is observed through a telescope. The arrangement is very similar to that employed by Professor Frost on the Bruce spectrograph. A finder of 4 m focal length attached to the tube of the large reflector is used to bring the star within the field of view. The observer keeps the star upon the slit by means of slow-motion motors controlled by switch buttons arranged upon a fiber bar held in his hand. Similar buttons control a motor at the upper end of the telescope tube which moves the convex mirror inward or outward and thus enables the observer to correct for changes of focus during the night. If the large mirror has been protected throughout the day by the canopy, as is regularly the case, these changes are rarely of large amount unless there is a marked change of temperature during the night.

This brief description of the general features of the spectrograph

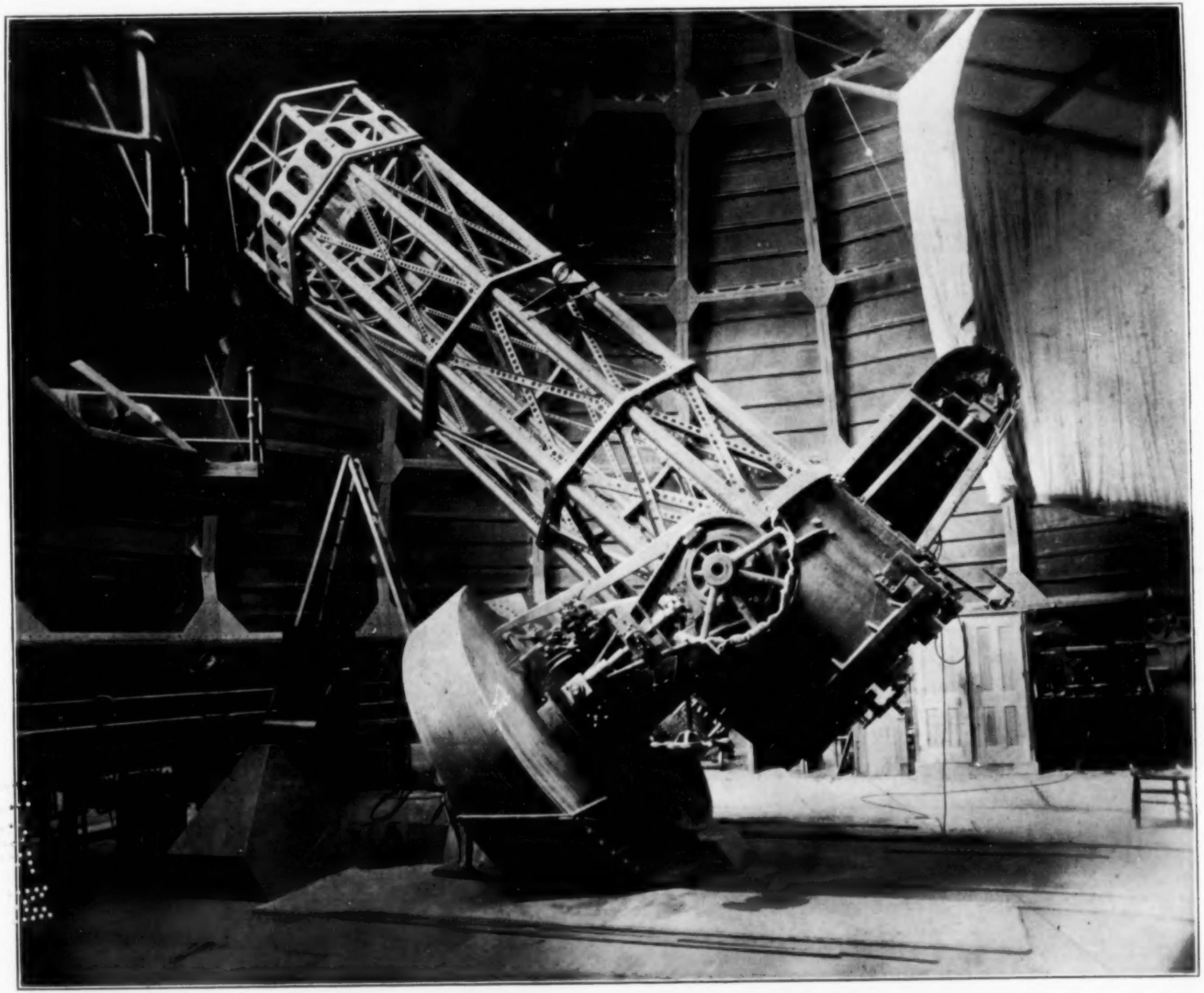
is perhaps sufficient to give a satisfactory conception of the instrument as a whole. Plate X shows the spectrograph attached to the 60-inch reflector. A part of the outer cover has been removed as well as both covers to the prism-box, so that the arrangement of the prisms and of the camera and collimating tubes is well shown. The tube through which the light reflected from the slit is observed is seen beneath the spectrograph in the lower right-hand corner of the photograph.

PROGRAM OF WORK AND EXPOSURE TIMES

A large part of the time of the spectrograph during the year it has been in operation has been devoted to a determination of the radial velocities of some selected lists of stars, mainly of types A and B, whose proper motions have been measured by Boss and whose velocities are of especial importance in studies of star streams. The lists have been prepared by Professor Kapteyn and consist of stars which for the most part lie between magnitudes 5.5 and 6.5,[1] although a few are brighter. The experience of numerous observers of stellar spectra has shown that by far the greater number of stars with spectra of types A or B can be studied to better advantage with moderate dispersion and linear scale than with high dispersion, on account of the diffuse and broad character of their lines. Some experiments with our spectrograph showed that an optical system consisting of two prisms and the 46 cm camera, or a single prism and the 102 cm camera, gave the most satisfactory results for the majority of the stars. Both combinations have been used and as between the two it is largely a question of the type of spectrum and conditions of seeing. For stars with numerous lines in their spectra the greater resolving power of the two-prism arrangement is preferable. For stars with few lines, however, the single prism is adequate, and the greater width of spectrum obtained with the long camera is an important advantage. In fact, under good conditions of seeing the time occupied in running the star's image along the slit sufficiently to obtain a measurable width of spectrum

[1] The magnitudes used in this article are those given in the "Preliminary General Catalogue of 6188 Stars for the Epoch 1900," by Lewis Boss, *Carnegie Institution of Washington Publication* No. 115. A comparison of these magnitudes with those of the Potsdam and the Harvard Photometry is given in the "Catalogue."

PLATE X



Sixty-Inch Reflecting Telescope of the Mount Wilson Solar Observatory with the Three-Prism Stellar Spectrograph Attached

is a considerable drawback to the use of the short camera. The linear scale at $H\gamma$ of the photographs obtained with the two arrangements is as follows:

Two prisms and short camera, 1 mm = 18.0 Ångströms
One prism and long camera, 1 mm = 15.7 Ångströms

The three prisms and long camera as used for the spectra of the brighter stars give a linear scale at $H\gamma$ of 1 mm = 5.2 Ångströms.

The exposure times with the spectrograph vary widely, of course, with the conditions of seeing. Under good conditions, when the silver surfaces of the telescope are bright, a fully timed negative of a star of type A or B of magnitude 6.0 on Boss's system may be obtained in one hour, when one prism and the long camera are employed. The exposure times with two prisms and the shorter camera are slightly less. Under average conditions the exposure times are somewhat longer, and under the poorest conditions of the winter season may be several times as long. Usually an exposure about one-fourth longer is given to stars of types F, G, K, and M than to stars of types A and B. The difference would be greater but for the fact that the density of negative required for satisfactory measurement is less in the case of spectra containing numerous lines than for those of types A and B. Under very good conditions of seeing, a fully timed negative of *Groombridge 1830* (Mag. 6.5, Spectrum G) has been obtained in 75 minutes with a slit-width of 0.050 mm. A narrower slit has been employed upon some nights of exceptionally fine seeing, but this width has been used for a majority of the photographs.

METHOD OF REDUCTION

The range of spectrum in good focus upon the negatives and upon which measures may be made extends from about λ 4250 to λ 4900. As a rule in the case of stars of types A and B the measures are limited to the portion between $H\gamma$ and $H\beta$. Within this region fall several of the most important helium lines, the magnesium line λ 4481, and a large number of enhanced metallic lines whose appearance is so characteristic of a portion of the A-type stars. The fact that $H\gamma$ and $H\beta$ are almost without exception measurable lines in the spectra of A- and B-type stars has led us to the use of auxiliary

tables which have enabled us to save much time in the reduction of the photographs.

The method employed is that used by Professor Frost and several other observers, in accordance with which each negative is reduced independently from measures of three standard lines in the comparison spectrum. It has the marked advantage of requiring no adjustment of the measures on account of changes of focus of the camera or collimator or variation in the scale of the spectrum due to the different temperatures of the prism-train. The chief objection to it is the amount of time required to compute the constants of the Cornu-Hartmann formula for each plate. For the reduction of our spectrograms we have constructed tables giving the values of these constants for the entire range of variation of scale which may occur. This is accomplished in the following way. Two suitable comparison lines are selected at the extremities of the region measured and another line intermediate between them, and these lines are measured upon all of the photographs. The lines selected for our purposes are $\lambda\,4337.216$ near $H\gamma$, $\lambda\,4859.928$ near $H\beta$, and the intermediate line $\lambda\,4531.327$. Let us indicate these lines by λ'', λ, and λ', and the corresponding readings of the comparator by S'', $S+\delta$, and S', as follows:

4859.928	......λ	$S+\delta$
4531.327	......λ'	S'
4337.216	......λ''	S''

The solution of the Hartmann formula gives for the values of the constants:

$$\lambda_0=\lambda-\frac{a(\lambda-\lambda'')-b(\lambda-\lambda')}{a-b+\delta(\lambda'-\lambda'')}\,,$$

$$S_0=\frac{aS'-bS''-\delta S'(\lambda-\lambda')+\delta S''(\lambda-\lambda'')}{a-b+\delta(\lambda'-\lambda'')}\,,$$

$$C=(\lambda''-\lambda_0)(S''-S_0),$$

where $a=(\lambda-\lambda')\,(S''-S)$ and $b=(\lambda-\lambda'')\,(S'-S)$.

If we develop the values λ_0 and S_0 into series we obtain:

$$\lambda_0=\lambda-\alpha(1-\beta\delta+\beta^2\delta^2-\ .\ .\ .\ .)$$

$$S_0=c-d\delta+d^2\delta^2-\ .\ .\ .\ .$$

in which α, β, c, and d are constants. Both series are rapidly convergent for small values of δ. It is, of course, a simple matter to

adjust all of the spectrograms under the comparator in such a way that the reading upon λ 4337 shall always be the same, or S'' constant. Then for any value of $S'-S''$ we may obtain the values of λ_0 and S_0 corresponding to a set of readings $S+\delta$ from the series given above. Since δ never exceeds 0.025 mm for our photographs the term δ^3 is negligible, and if extreme values of λ_0 and S_0 are known, all intermediate values may be obtained by simple interpolation in which the second differences are constant. To illustrate the construction of a page of the tables we may consider a specific case. Let the readings be:

4859.928..........56.500$+\delta$
4531.327..........41.317
4337.216..........30.000

A range in δ of 0.025 will readily take care of all the differences which may arise in the reading upon λ 4859 for a given reading upon λ 4531. Accordingly three Hartmann formulae are solved for readings of 56.500, 56.512, and 56.525. With these values of λ_0, S_0, and C we derive the values of the first and second differences for purposes of interpolation, and are enabled to compute rapidly the values of λ_0, S_0, and C corresponding to 56.501, 56.502, etc. This page of the table corresponds to the argument $S'-S''=$ 11.317. For the value $S'-S''=11.318$ a second page is computed, and the process is repeated throughout the range of scale which may occur. The measurement of a few photographs taken at different temperatures gives sufficient knowledge of the mean values about which the table should be constructed. In the case of our own photographs a table consisting of forty pages has been found sufficient to care for the entire range of variation of scale observed, and a table of this size was completed by a single computer with the aid of a calculating machine in about six days.

The constants of reduction for a given spectrogram being obtained by inspection from this table, the wave-lengths of the stellar and comparison lines are computed in the usual way from the constants, and the stellar wave-lengths are corrected according to the deviations of the comparison lines. The complete reduction of a spectrogram containing fifteen stellar and comparison lines occupies about twenty minutes.

TABLE I

STARS OF VARIABLE RADIAL VELOCITY

Boss Number Designation R.A. (1910) Dec. (1910)	Mag. and Type	No. of Plate	Observer	Date	G. M. T.	Radial Velocity	Measured by	Quality	Remarks
					h m	km			
Boss 67	5.6	29	A.	1910, Dec. 20	16 17	+ 5	L.	Fair	
Groom. 58	B 5	36	P.	1910, Dec. 21	15 32	− 35	L.A.		
$0^h19^m.4$		161	A.P.	1911, Jan. 21	16 18	0	L.A.		
$+51°31'$		944	K.	1911, Dec. 11	15 19	+ 2	L.E.		
		988	A.	1912, Jan. 7	15 34	− 4	L.		
Boss 68	5.6	25	A.	1910, Dec. 18	16 14	− 18	L.	Poor	
12 Cassiop.	B 9	37	P.	1910, Dec. 21	16 42	− 49	L.A.		
$0^h19^m.8$		160	A.	1911, Jan. 21	15 34	− 12	L.A.		
$+61°20'$		934	K.	1911, Dec. 9	17 10	+ 5	L.E.		
		1009	A.	1912, Jan. 11	15 24	− 19	L.		
Boss 91	5.4	624	P.	1911, Aug. 13	22 15	− 3	L.E.	Fair	
49 G Celi	A 2	859	K.	1911, Oct. 13	19 42	+ 15	L.E.A.		
$0^h25^m.9$		915	K.	1911, Nov. 5	16 48	+ 32	L.E.A.		
$-24°17'$									
Boss 159	5.5	30	A.	1910, Dec. 20	17 08	+ 18	L.	Fair	
23 Cassiop.	B 9	38	P.	1910, Dec. 21	17 40	− 30	L.A.		
$0^h41^m.7$		135	A.	1911, Jan. 18	15 22	− 16	L.A.		
$+74°21'$		874	A.	1911, Oct. 30	20 05	+ 3	L.E.K.		
		935	K.	1911, Dec. 9	18 16	+ 5	L.E.		
		981	K.	1912, Jan. 5	15 55	+ 11	L.E.		
Boss 412	5.7	138	B.	1911, Jan. 18	17 37	+ 77	L.A.	Poor	
1 Persei	B 3	876	A.	1911, Oct. 30	22 05	− 12	L.A.		
$1^h46^m.1$		945	K.	1911, Dec. 11	16 20	− 6	L.E.		
$+54°42'$		989	A.	1912, Jan. 7	17 40	− 23	L.E.		

Boss 425	5.2	20	A.	1910, Dec. 17	15 30	+ 12	L.A.	Good	
ω Cassiop.	B 9	139	B.	1911, Jan. 18	18 42	− 46	L.A.		
$1^h49^m.0$		148	A.	1911, Jan. 19	18 25	− 44	L.A.		
$+68°15'$		995	A.	1912, Jan. 8	17 00	− 41	L.E.		
Boss 522	5.4	710	K.	1911, Sep. 9	21 37	− 40	L.E.	Fair	Probably composite spectrum
62 Andromedae	A	766	K.	1911, Sep. 17	21 18	− 21	L.E.		
$2^h13^m.5$		801	A.	1911, Oct. 6	21 45	− 22	L.E.A.K.		
$+46°58'$									
Boss 641	5.5	70	P.	1910, Dec. 24	16 38	− 9	L.A.	Good	
π Arietis	B 5	146	A.	1911, Jan. 19	16 48	− 12	L.A.		
$2^h44^m.2$		209	A.	1911, Feb. 10	15 51	+ 32	L.E.		
$+17°5'$		951	K.	1911, Dec. 12	15 50	+ 7	L.E.		
Boss 731	5.7	711	K.	1911, Sep. 9	22 39	− 4	L.E.	Good	Probably composite spectrum
Piazzi 9	A	767	K.	1911, Sep. 17	22 19	− 8	L.E.		
$3^h9^m.8$		820	A.	1911, Oct. 8	21 46	− 17	L.E.A.		
$+30°13'$		860	K.	1911, Oct. 13	21 30	− 4	L.E.A.		
		959	K.	1911, Dec. 14	18 00	+ 2	L.E.		
Boss 740	5.5	12	A.	1910, Dec. 16	17 02	+ 23	L.A.	Poor	
30 Persei	B 5	32	A.	1910, Dec. 20	18 42	+ 12	L.A.		
$3^h11^m.7$		40	P.	1910, Dec. 21	19 28	− 6	L.A.		
$+43°42'$		77	P.	1911, Jan. 7	15 15	− 14	L.A.		
		87	P.	1911, Jan. 8	14 36	+ 11	L.A.		
Boss 796	6.1	33	A.	1910, Dec. 20	19 40	+ 24	L.A.	Poor	
Brad. 480	B 8	41	P.	1910, Dec. 21	20 30	+ 2	L.A.		
$3^h24^m.2$		97	P.	1911, Jan. 11	17 43	− 1	L.A.		
$+47°48'$		107	P.	1911, Jan. 12	18 01	+ 13	L.A.		
Boss 841	5.7	51	P.	1910, Dec. 22	18 12	− 59	L.A.	Poor	
13 Tauri	B 8	177	A.	1911, Feb. 7	16 12	+ 9	L.W.		
$3^h37^m.1$		997	A.	1912, Jan. 8	19 05	+ 8	L.E.		
$+19°25'$									

TABLE I—*Continued*

Boss Number Designation R.A. (1910) Dec. (1910)	Mag. and Type	No. of Plate	Observer	Date	G. M. T.	Radial Velocity	Measured by	Quality	Remarks
					h m	km			
Boss 857	5.4	62	P.	1910, Dec. 23	17 28	+ 61	L.A.	Poor	
24 Eridani	B 8	110	P.	1911, Jan. 12	18 44	+ 75	L.A.		
$3^h39^m.9$		127	B.	1911, Jan. 17	16 24	+ 41	L.A.		
$-1°29'$									
Boss 878	5.3	724	A.	1911, Sep. 11	22 40	− 19	L.E.	Good	
42 Persei	A 2	790	A.	1911, Oct. 5	23 14	+ 13	L.E.A.		
$3^h43^m.8$		891	A.	1911, Nov. 1	21 25	− 7	L.		
$+32°49'$		967	K.	1911, Dec. 30	18 42	− 40	L.E.K.		
Boss 992	5.6	35	A.	1910, Dec. 20	21 59	− 35	L.A.	Poor	
Groom. 809	B 3	42	P.	1910, Dec. 21	21 46	+ 3	L.A.		
$4^h13^m.4$		180	A.	1911, Feb. 7	18 41	− 42	L.W.A.		
$+50°42'$		271	A.	1911, Mar. 15	15 29	− 7	L.A.		
		1007	A.	1912, Jan. 9	19 35	− 40	L.E.		
Boss 1076	4.4	826	K.	1911, Oct. 9	21 48	− 43	L.E.A.	Good	
88 Tauri	A 2	904	K.	1911, Nov. 3	22 31	− 40	L.E.A.		
$4^h30^m.7$		984	K.	1912, Jan. 5	19 54	+ 71	L.E.		
$+9°59'$									
Boss 1249	6.0	211	A.	1911, Feb. 11	18 06	+ 61	L.	Good	Two spectra present, B 5 and probably A 3. Measures on stronger spectrum B 5
Pulk. 801	B 5 p	272	A.	1911, Mar. 15	16 30	+ 64	L.A.W.		
$5^h10^m.4$		281	A.	1911, Mar. 16	16 26	+ 53	L.A.		
$+34°13'$		309	P.	1911, Mar. 24	16 20	+ 63	L.W.		
		936	K.	1911, Dec. 9	20 38	+ 53	L.E.		
		998	A.	1912, Jan. 8	20 13	+ 64	L.E.		
Boss 1349	5.6	64	P.	1910, Dec. 23	19 18	+134	L.A.	Fair	
Green. 412 (1860)	B 2	112	P.	1911, Jan. 12	21 28	−138	L.A.		
$5^h28^m.9$									
$-1°13'$									

Boss 1607	5.7	877	A.	1911, Oct. 30	23 02	− 55.8	L.E.A.	Good	
Groom. 1149	A 5	910	K.	1911, Nov. 4	22 08	+ 21.2	L.E.A.		
6^h18^m8		949	K.	1911, Dec. 11	23 28	− 75.8	L.E.		
$+56°20'$									
Boss 1906	5.9	68	P.	1910, Dec. 23	23 10	− 80	L.A.	Fair	Two spectra present
Brad. 1056	B 8	103	P.	1911, Jan. 11	23 40	+ 90	L.A.		
7^h15^m5		132	B.	1911, Jan. 17	21 58	− 6	L.A.		
$+55°29'$									
Boss 2400	5.3	930	K.	1911, Dec. 8	23 11	− 46	L.E.	Good	
62 Cancri	A 3	969	K.	1911, Dec. 30	23 08	− 35	L.E.K.		
8^h52^m2		1025	K.	1912, Jan. 24	21 58	− 13	L.E.A.		
$+15°40'$									
Boss 2407	4.4	923	K.	1911, Dec. 7	1 08	− 54	L.E.	Good	
a Cancri	A 3	931	K.	1911, Dec. 8	23 56	− 59	L.E.		
8^h53^m6		1026	K.	1912, Jan. 24	22 50	− 21	L.E.A.		
$+12°12'$									
Boss 2451	5.6	191	A.	1911, Feb. 8	19 24	+ 14	L.E.A.	Poor	
19 Hydrae	B 8	202	A.	1911, Feb. 9	19 38	+ 18	L.W.A.		
9^h4^m3		256	A.	1911, Mar. 11	18 16	+ 46	L.A.		
$-8°14'$		392	A.	1911, May 9	16 10	+ 4	L.A.		
Boss 2866	5.4	75	P.	1910, Dec. 25	0 03	− 2	L.A.	Poor	
42 Leo. Min.	B 9	104	P.	1911, Jan. 12	1 20	+ 40	L.A.		
10^h40^m9		157	A.	1911, Jan. 20	0 40	− 9	L.A.		
$+31°9'$									
Boss 3123	5.7	950	K.	1911, Dec. 21	0 32	− 90	L.E.	Fair	
95 Leonis	A 2	1027	K.	1912, Jan. 25	0 01	+ 7	L.E.A.		
11^h51^m0									
$+16°9'$									

TABLE I—*Continued*

Boss Number Designation R.A. (1910) Dec. (1910)	Mag. and Type	No. of Plate	Observer	Date	G. M. T.	Radial Velocity	Measured by	Quality	Remarks
					h m	km			
Boss 3138	5.4	183	A.	1911, Feb. 7	22 34	+ 16	L.W.	Good	
31 Crateris	B 3	258	A.	1911, Mar. 11	20 26	−116	L.A.		
$11^h56^m.2$		311	P.	1911, Mar. 24	20 15	+ 85	L.A.		
$-19°9'$		348	A.	1911, Apr. 12	18 56	− 21	L.E.		
Boss 3546	6.4	302	B.	1911, Mar. 19	22 22	+ 11	L.A.	Poor	
85 Virginis	B 9	312	P.	1911, Mar. 24	22 00	− 93	L.A.		
$13^h40^m.7$									
$-15°19'$									
Boss 3915	5.6	363	A.	1911, Apr. 14	21 30	+ 16	L.E.A.	Poor	
50 Boötis	B 9	509	A.	1911, July 6	18 38	− 3	L.E.A.		
$15^h18^m.2$		539	B.	1911, July 11	16 41	− 41	L.E.A.		
$+33°15'$									
Boss 3944	5.7	303	P.	1911, Mar. 19	23 55	− 23	L.E.A.	Poor	Possibly composite spectrum
35 Librae	B 3	314	P.	1911, Mar. 24	23 39	− 19	L.A.		
$15^h27^m.8$		489	A.	1911, June 17	15 57	+ 30	L.A.E.		
$-16°33'$									
Boss 3993	5.3	232	B.	1911, Feb. 17	0 30	+ 3	L.W.	Good	
χ Serpentis	A 3 p	333	P.	1911, Apr. 9	20 47	− 4	L.		
$15^h37^m.6$		478	A.	1911, June 15	16 10	+ 36	L.A.		
$+13°8'$									
Boss 4097	5.8	359	A.	1911, Apr. 13	22 22	− 13	L.	Poor	
11 Scorpii	B 9	496	A.	1911, July 4	17 45	− 30	L.E.A.		
$16^h2^m.6$		527	A.	1911, July 9	16 40	− 6	L.E.		
$-12°30'$		533	A.	1911, July 10	17 19	− 50	L.E.A.		

Boss 4353 Piazzi 303 $17^h3^m.6$ $-0°58'$	6.2 A	442 464 497 540	B. P. A. B.	1911, June 10 1911, June 11 1911, July 4 1911, July 11	21 26 19 48 19 07 17 56	−14 −21 −39 −8	L.A. L.E.A. L.A. L.E.A.	Fair	
Boss 4402 *70 Herculis* $17^h17^m.2$ $+24°35'$	5.5 A	674 726 812	B. K. A.	1911, Sep. 6 1911, Sep. 12 1911, Oct. 8	60 00 15 22 15 10	−18 −26 −3	L.E. L.E.A. L.E.A.	Fair	
Boss 4643 *108 Herculis* $18^h17^m.5$ $+29°49'$	5.7 A 3	660 714 813 822	B. K. A. K.	1911, Sep. 4 1911, Sep. 10 1911, Oct. 8 1911, Oct. 9	16 07 15 35 16 09 15 25	−94 −62 −28 +38	L.E.A. L.E. L.E.A. L.E.A.	Good	
Boss 4867 Piazzi 318 $19^h3^m.0$ $+28°29'$	5.7 A 3	667 728 906	B. K. K.	1911, Sep. 5 1911, Sep. 12 1911, Nov. 4	16 59 16 36 15 00	−42 −6 −24	L.E.A. L.E.A. L.E.K.	Poor	Probably composite spectrum
Boss 4947 *2 Sagittae* $19^h20^m.3$ $+16°46'$	6.2 A 3	591 879	B. A.	1911, Aug. 9 1911, Oct. 31	18 21 15 46	+61 +18	L.E. L.E.A.	Good	
Boss 5042 *ψ Aquilae* $19^h40^m.4$ $+13°5'$	6.4 A p	629 720 763	P. K. K.	1911, Aug. 14 1911, Sep. 11 1911, Sep. 17	19 18 17 29 17 20	−27 −2 +16	L.E.A. L.E.A. L.E.	Good	
Boss 5113 Groom. 2984 $19^h54^m.1$ $+40°8'$	5.6 B 3	518 886	A. A.	1911, July 7 1911, Nov. 1	21 44 15 32	−65 +23	L.E.A. L.E.A.	Poor	

TABLE I—*Continued*

Boss Number Designation R.A. (1910) Dec. (1910)	Mag. and Type	No. of Plate	Observer	Date	G. M. T.	Radial Velocity	Measured by	Quality	Remarks
					h m	km			
Boss 5178	6.0	519	A.	1911, July 7	22 44	− 16	L.E.A.	Poor	$H\beta$ doubly reversed
20 Vulpeculae	B 8 p	536	A.	1911, July 10	20 48	− 32	L.E.A.		
$20^h 8^m.2$		552	B.	1911, July 13	20 36	− 37	L.E.A.		
$+26°13'$		796	A.	1911, Oct. 6	17 50	− 15	L.A.K.		
Boss 5211	5.8	691	B.	1911, Sep. 7	18 58	+ 2	L.E.A.	Fair	
36 Cygni	A	738	K.	1911, Sep. 14	18 13	− 27	L.E.A.		
$20^h 15^m.1$		823	K.	1911, Oct. 9	17 03	− 10	L.E.A.		
$+36°43'$									
Boss 5292	5.5	706	K.	1911, Sep. 9	17 51	+ 45	L.E.A.	Good	
ι Delphini	A 2	770	K.	1911, Sep. 18	18 06	+ 18	L.E.		
$20^h 33^m.5$		894	A.	1911, Nov. 2	15 08	+ 24	L.E.A.		
$+11°4'$									
Boss 5322	5.8	692	B.	1911, Sep. 7	20 12	− 40	L.E.	Good	
Groom. 3258	B 9	755	K.	1911, Sep. 16	17 59	− 25	L.E.		
$20^h 38^m.7$		914	K.	1911, Nov. 5	15 34	− 16	L.E.A.		
$+41°24'$									
Boss 5573	6.2	593	B.	1911, Aug. 9	21 25	+ 33	L.E.	Fair	
76 Cygni	B 9	640	P.	1911, Aug. 15	21 48	− 7	L.E.		
$21^h 38^m.0$									
$+40°18'$									
Boss 5581	6.2	588	B.	1911, Aug. 8	20 40	+ 23	L.E.	Poor	
45 Capricorni	A 2	621	P.	1911, Aug. 13	19 40	+ 45	L.E.		
$21^h 39^m.1$		654	P.	1911, Aug. 17	19 34	− 3	L.E.A.		
$-15°10'$									

Boss 5692	5.9	852	K.	1911, Oct. 12	18 23	− 55	L.E.A.	Fair	$H\beta$ bright
25 Pegasi	B 5 p	887	A.	1911, Nov. 1	16 48	− 59	L.E.A.		
$22^h 3^m.6$		954	K.	1911, Dec. 13	15 32	− 36	L.E.		
$+21°16'$									
Boss 5738	6.4	601	B.	1911, Aug. 10	22 08	− 15	L.E.A.	Poor	
Br. 2938	B 8	858	K.	1911, Oct. 13	17 36	+ 28	L.E.A.		
$22^h 11^m.0$									
$+62°43'$									
Boss 5833	5.9	608	B.	1911, Aug. 11	22 16	− 39	L.E.A.	Poor	$H\beta$ unsymmetrically reversed
8 Lacertae	Oe p	632	P.	1911, Aug. 14	22 22	+ 7	L.E.		
$22^h 31^m.9$		807	A.	1911, Oct. 7	19 44	+ 4	L.A.K.		
$+39°10'$									
Boss 5848	5.3	732	K.	1911, Sep. 12	21 42	+ 40	L.E.A.	Poor	
30 Cephei	B 9	784	A.	1911, Oct. 5	18 24	− 5	L.E.A.K.		
$22^h 35^m.5$		866	K.	1911, Oct. 14	17 30	+ 16	L.E.A.		
$+63°7'$									
Boss 5856	5.4	648	P.	1911, Aug. 16	23 00	+ 3	L.E.	Good	
12 Lacertae	B 2	702	K.	1911, Sep. 8	21 49	+ 6	L.E.A.		
$22^h 37^m.5$		756	K.	1911, Sep. 16	19 03	− 8	L.E.		
$+39°45'$		786	A.	1911, Oct. 11	19 34	− 43	L.E.		
Boss 6075	5.4	602	B.	1911, Aug. 10	23 28	+ 37	L.E.A.	Poor	
18 Andromedae	B 8	633	P.	1911, Aug. 14	23 30	− 3	L.E.		
$23^h 34^m.8$		659	P.	1911, Aug. 18	0 07	− 1	L.E.A.		
$+49°58'$		799	A.	1911, Oct. 6	19 56	+ 1	L.E.A.		
Boss 6142	6.2	888	A.	1911, Nov. 1	18 12	− 53	L.E.A.	Fair	Spectrum probably composite
Br. 3184	Oe p	987	A.	1912, Jan. 6	15 54	− 11	L.E.		
$23^h 51^m.0$		1003	A.	1912, Jan. 9	15 12	−133	L.		
$+56°55'$									

SOME RESULTS

A list of fifty spectroscopic binaries.—We have found the above 50 stars mainly of types A and B to have variable velocities in the line of sight. The initial given in the column headed "Observer" refers to Messrs. Adams, Babcock, Kohlschütter, and Pease, and in the column "Measured by" to Miss Lasby, Miss Ensign, Miss Waterman, and Messrs. Kohlschütter and Adams. The type of spectrum given is in most cases from our own observations. The column in the table preceding "Remarks" indicates roughly the general character of the spectrum for purposes of measurement. There is evidence of complexity of the hydrogen lines in the spectra of many of these stars, and no doubt more would be found were the density of the negatives made somewhat less. As a rule, however, considerable density of the continuous spectrum aids in the measurement of the broad hazy lines characteristic of the spectra of most of these stars.

In addition to the stars given in Table I we have secured observations which agree in confirming the variability of velocity of the following stars announced from other observatories:

Name	R. A. 1910	Dec. 1910	Mag.	Observatory
25 Serpentis	15^h41^m4	$-\ 1°31'$	5.6	Yerkes
χ Ophiuchi	16 21.8	$-18°14'$	4.8	Lick
ζ^1 Lyrae	18 41.7	$+37°31'$	4.4	Lick
δ^1 Lyrae	18 50.6	$+36°52'$	5.7	Yerkes
θ Aquilae	20 6.7	$-\ 1°\ 5'$	3.2	Meudon
6 Lacertae	22 26.6	$+42°40'$	4.5	Yerkes

Stars with bright hydrogen lines.—The stars *20 Vulpeculae*, *25 Pegasi*, and *8 Lacertae* in Table I have one or more hydrogen lines bright. In *χ Ophiuchi*, as has been announced by Professor Campbell, both $H\gamma$ and $H\beta$ are bright. The following stars also have bright hydrogen lines:

Name	R. A. 1910	Dec. 1910	Mag.	Bright Lines
11 Camelopardalis	4^h58^m3	$+58°51'$	5.3	$H\gamma$ and $H\beta$
165 G Canis Majoris	7 20.6	$-16°\ 1'$	5.3	$H\gamma$ and $H\beta$
25 Vulpeculae	20 18.2	$+24°10'$	5.7	$H\beta$

TABLE II

STARS WITH GREAT RADIAL VELOCITIES

Designation R.A. (1910) Dec. (1910)	Mag. Spectrum	No. of Plate	Observer	Date	Radial Velocity	Mean Radial Velocity	Velocity in Space	Angle to Line of Sight
					km	km	km	
Lal. 4855	7.2	β 74	A.	1910, Jan. 18	−120	−120	186	130°
$2^h33^m.3$	G							
$+30°28'$								
Lal. 5761	8.0	β 75	A.	1910, Jan. 18	−156			
$3^h3^m.1$	F	β 91	A.	1910, Feb. 18	−153			
$+26° 0'$		β 104	A.	1910, Feb. 21	−150	−153	188	144°
Groom. 864	7.3	β 81	A.	1910, Jan. 21	+103			
$4^h35^m.2$	G	β 86	A.	1910, Feb. 17	+102			
$+41°58'$		β 97	A.	1910, Feb. 20	+101			
		β 105	A.	1910, Feb. 21	+ 97			
		γ 237	P.	1911, Feb. 18	+100.8			
		γ 245	P.	1911, Feb. 21	+103.7	+101	163	52°
Groom. 1830	6.5	γ 194	A.	1911, Feb. 8	− 99.7			
$11^h47^m.7$	G	γ 247	P.	1911, Feb. 21	− 99.2			
$+38°23'$		γ 362	A.	1911, Apr. 14	− 96.2			
		γ 399	A.	1911, May 11	− 95.8	− 97.7	343	107°
Lal. 28607	7.3	γ 323	P.	1911, Apr. 7	−166			
$15^h38^m.2$	A	γ 368	A.	1911, Apr. 15	−168			
$-10°39'$		γ 446	B.	1911, June 7	−172			
		γ 516	A.	1911, July 7	−175	−170	173	128°
31 b Aquilae	5.2	γ 335	P.	1911, Apr. 9	− 95.9			
$19^h20^m.7$	G	γ 377	A.	1911, Apr. 16	− 97.0	− 96.4	119	144°
$+11°45'$								
Lal. 37120–1	6.6	β 227	A.	1910, May 20	−162			
$19^h30^m.1$	G	β 235	A.	1910, May 21	−163			
$33° 0'$		γ 364	A.	1911, Apr. 14	−161.9			
		γ 409	P.	1911, May 15	−161.8	−162	167	166°

Some stars with great radial velocities.—In the course of our observations of some stars of large proper motions with known parallaxes we have found a few stars with very great radial velocities. Most of these had previously been observed with the small focal plane spectrograph and approximate velocities determined. Accordingly in Table II the spectrograms obtained with the focal plane instrument are indicated by the series letter β and those with the large spectrograph by γ. The values obtained with the small spectrograph are of course subject to considerable uncertainty.

With the exception of *Groombridge 1830*, for which Professor Campbell has published a value of -95 km, no other observations are available for these stars. The star *Lalande 28607* is of especial interest because of its type of spectrum. No star of type A with a constant velocity approaching this in magnitude has been observed heretofore.

Since the parallaxes and the proper motions of these stars are known, a computation of their velocities and directions of motion in space becomes of interest. These are given in the last two columns of Table II, the requisite data being taken from the list of parallax determinations compiled by Kapteyn and Weersma.[1]

I am indebted for much assistance in connection with the results referred to in this communication. In particular I wish to express my appreciation to Mr. Pease for his great aid in the design of the spectrograph, many important features of which are due to his suggestions; to Mr. Babcock and Dr. Kohlschütter for observations with the instrument; and to Miss Lasby, Miss Ensign, and Miss Waterman for the difficult work involved in the measurement of the spectra.

MOUNT WILSON SOLAR OBSERVATORY
February 1912

[1] *Publications of the Astronomical Laboratory of Groningen*, No. 24.

THE EFFECT OF PRESSURE UPON ELECTRIC FURNACE SPECTRA

SECOND PAPER[1]

By ARTHUR S. KING

In a former paper[2] the writer reported the results of some preliminary experiments on the spectrum of the electric furnace when operated in an atmosphere of compressed gas. The displacements measured were chiefly for lines in two regions of the iron spectrum for a pressure of 9 atmospheres. The measurements, though not extensive enough to be given high weight, showed, when compared with such measurements of arc spectra under pressure as were available, that the lines in general were displaced much more in the furnace than in the arc at equal pressure.

It was obviously desirable to continue this investigation in such a way as to establish in a definitive manner the leading characteristics of the furnace spectrum when under pressure, and it is believed that sufficient material is now on hand for this purpose. About one hundred furnace photographs have been made since the preliminary set, the spectra studied being those of iron for the regions λ 4200 to λ 4500 and λ 5200 to λ 5500, titanium from λ 4250 to λ 4600, and vanadium from λ 4050 to λ 4600. The range of pressures has been up to 24 atmospheres for the two regions of the iron spectrum, up to 16 atmospheres for the spectra of titanium and vanadium. The leading features studied have been as follows:

1. The rate of increase of displacement with pressure and the mean shift per atmosphere for various groups of lines which permitted measurements of considerable accuracy.

2. The pressure effect in absorption as obtained by passing white light through the furnace tube when under pressure.

3. A search for possible variation of displacement with temperature.

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 60.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 53; *Astrophysical Journal*, **34**, 37, 1911.

4. The observation of the effects due to large and small quantities of the radiating vapor, to the presence of foreign vapors, and to variation in the length of the column of vapor by the use of long and short tubes, the pressure being the same for these different conditions.

5. A comparison of the relative displacements of groups of lines with their response to temperature excitation and with their behavior in the magnetic field.

6. A consideration in the case of a few iron lines of the variation of displacement with wave-length.

7. Attention is directed to what is apparently a fundamental difference in the structure of arc and furnace lines which may explain the difference in absolute displacement given by the two sources.

EXPERIMENTAL METHOD

The work has been carried on in general according to the method described in the previous paper, with such improvements as experience showed to be feasible. The photographs were made in the second order of the vertical Littrow spectrograph in the Pasadena laboratory, the scale for the regions studied ranging from 0.93 to 0.96 Å per mm. The furnace was operated in vacuum to give the comparison spectrum, which was placed on each side of the pressure photograph by means of the occulting plate above the slit. This exposure with the furnace in vacuum was taken partly before and partly after the pressure photograph, the second exposure being made with increased length of slit on each side, so that the comparison photograph appears as the superposition of the two exposures, with weak extensions due to the second. This gave an exceedingly delicate test for instrumental displacement during the making of the complete photograph, better than is given by a double exposure with slit unchanged in length since the fainter extensions sometimes showed a very slight lack of continuity when the superposed portion of the line did not appear to suffer in sharpness.

The tubes used in the furnace, except for the special tests at the close of the investigation, were of Acheson graphite, 30.5 cm long, 12.5 mm inside diameter, and either 19 or 20.5 mm outside diam-

eter, 20.5 cm being heated between the graphite contact blocks which led in the current. The tube was protected by a split graphite tube and by carborundum powder outside of this.

For the compressed gas, both carbon dioxide and air were used, the latter for most of the work, as it gave better results than carbon dioxide, especially for pressures above 16 atmospheres. The writer was surprised to find that the oxygen furnished by the air seemed to be less than that given off by dissociation of the carbon dioxide when in contact with the hot tube and jacketing materials, as the tubes lasted better in air and less of the white smoke was generated which always proved very disturbing with carbon dioxide on account of weakening the light and clouding the window. A very efficient method of jacketing has been devised, so that there was little circulation of gas about the exterior of the tube and it wore thin slowly. As a rule the tube was renewed in preparation for each photograph which involved a run of the furnace under pressure and two comparisons in vacuum, but occasionally a tube could be used longer at moderate temperatures. In one case the same tube was used for three successive experiments, being heated for a total of $2^h\ 46^m$ in air at 16 atmospheres, besides comparisons in vacuum aggregating $1^h\ 6^m$. The tubes appear to be much more subject to oxidation outside than inside, the oxygen entering the tube apparently passing into combination before it reaches the highly heated portion.

The best results were obtained for temperatures which gave readings of 2200° to 2400° C. when a Wanner pyrometer was directed at the wall of the interior of the tube. The temperature of the radiating vapor is necessarily lower than this by an unknown amount, since the temperature of the graphite wall, obtained either in this way or by the melting-point method, must be higher than that of the inclosed vapor.

The pressure was measured by a new calibrated gauge reading to 500 pounds. Two other gauges, which were used in former work and by Mr. Gale with the pressure arc, showed a close agreement with this gauge except at the beginning of their scales.

When the carborundum jacket was used, there was always a certain amount of vapor, especially at the higher pressures, which

condensed as a white powder on the water-cooled metal parts. This was not tested chemically but was probably an oxide of some constituent of the carborundum. As has been noted, there was more of this vapor when compressed carbon dioxide was employed. Near the end of the investigation, it was desired to try the effect of foreign vapors purposely introduced and also of different lengths of the column of radiating vapor. In both cases this oxide from the jacketing would have complicated the conditions, so the experiments were made without any protection around the tube. Naturally, there was then a more rapid wearing-away of the tube and a very rapid loss of the heat to the water-cooled chamber and electrode pipes, requiring a large increase in the electric energy to keep up the temperature. It was possible, however, to make the desired series of experiments under these conditions for a pressure of 8 atmospheres.

Tubes for which the heated portion was only 51 or 64 mm long were used by setting the two contact blocks at the proper points along the copper-pipe electrodes. Other tubes with a total length of 35.5 cm, 25.5 cm being heated, were also employed.

A new method of studying the pressure effect, for which the furnace is especially adapted, was carried out by obtaining the lines under pressure as absorption lines. The comparison spectrum was obtained as usual, in emission, with the furnace in vacuum before and after the pressure exposure. For the pressure photograph a parallel beam of white light from a projection arc was directed by means of a short-focus lens into the window of the furnace opposite the spectrograph. This light passed through the vapor in the furnace tube, which was radiating under pressure, and thence to the spectrograph. Absorption lines are thus obtained which can be made very narrow if the continuous spectrum is strong. The temperature of the furnace tube may be low if only the stronger lines are desired, and the exposure time is much less than is required for the same lines in emission. The pressure displacements, as will be shown later, are in good agreement with those obtained when the tube is strongly excited so as to give self-reversed lines. The method promises to be very useful as a supplementary one, especially for spectra such as titanium, where a large number of lines are easily

produced by the furnace but do not readily show self-reversal. The edges of the absorption lines are liable to be somewhat ragged as the result of the large variation in temperature from the middle to the two ends of the furnace tube, with attendant differences in density of the vapor. A strong continuous spectrum will remedy this to a large extent. Care must also be taken when examining lines which are also given as sharp emission lines by impurities in the carbons of the arc, since if the pressure displacement be small, the violet side of the absorption line is affected by the presence of the bright line.

In measuring the displacements, a series of four or six settings was made on the comparison line and a like number on the line displaced by pressure. The plate was then reversed in the machine and a similar set taken in the opposite direction. All plates of sufficiently good quality were measured by the writer on a small Gaertner comparator and most of them also by Miss Sheldon.

RESULTS

For the purpose of establishing the main phenomena of the pressure effect for the furnace, a set of lines was selected in the iron, titanium, and vanadium spectra which can be measured with fair precision at various pressures. As a rule (the exceptions usually being noted in the tables) only lines for iron and vanadium are measured which are distinctly reversed. For titanium the lines were measured unreversed and in absorption. The list is thus limited to lines appearing at the lower furnace temperatures, the self-reversal being given by the absorption of the cooler vapor at the ends of the tube. The former paper showed that the number of iron lines which can be measured in the furnace spectrum, especially at pressures less than 10 atmospheres, is quite comparable with the number measurable in the arc, and this is true also for titanium and vanadium, but special conditions must be chosen for various sets of lines, since on any one plate only a relatively small number of lines will yield measurements of high weight.

As there is always a certain amount of widening to pressure lines, which in general increases with the pressure and often involves dissymmetry in the widening, a reversed line is preferable for measure-

ment, provided the reversal is narrow. If there is a tendency for the line to widen toward one side, the reversal may be expected to take part in this, but on account of its relatively small width, its position as measured cannot differ from the true position of the maximum by so great an amount as may easily happen when an unreversed and rather wide line is measured.

It is characteristic of reversed lines in furnace spectra that they do not have clean-cut edges to the reversals. There is a slow gradient in temperature and vapor-density from the center to each end of the tube which results in a gradual shading of the sides of the reversal. For this reason, personal judgment may enter to a considerable degree in making settings on the lines, and the opportunity for this increases if the reversals are not very narrow. Differences of considerable magnitude in the measurements for single lines have occasionally been observed which may fairly be ascribed to this cause. However, all of the conclusions to be drawn from the material in this paper are based on mean displacements for sets of lines which show shifts of the same order of magnitude, and such means do not appear to be greatly affected by personal differences. As a test, the mean displacements were compared for ten good plates measured by Miss Sheldon and myself. These plates embraced the spectra of all three elements and were for various pressures and different types of lines. The differences ranged from 9 per cent for unreversed titanium lines to exact agreement for a plate containing over 20 reversed vanadium lines. Most of the differences were well under 5 per cent and about equally divided as to which observer obtained the higher values. A large proportion of the whole number of plates was of about the quality of those compared, so that it seems highly improbable that the mean values presented are affected in any vital degree by peculiarities in personal judgment.

It was desirable to look farther into the large differences between furnace and arc displacements for the same pressure, which were indicated by the preliminary observations. Instrumental differences, such as must occur for work carried out in different laboratories, have been largely eliminated by comparing the later furnace results with the values for arc displacements obtained by Gale and

Adams[1] in an investigation carried out with pressures which were used also for the furnace and with the same spectrograph. At the close of the pressure-arc investigation, the spectrograph was used by the writer with the same adjustments as to focus, thus insuring that the photographs, as regards scale and definition, should be as closely comparable as possible. The change from the arc arrangements thus consisted in turning the vertical spectrograph around until its mirror faced the furnace. The image of the interior of the tube was focused on the slit, giving a cone of light slightly larger than the objective of the spectrograph. The focusing lens was never moved during the making of a pressure photograph with its two comparison exposures in vacuum.

The pressure values for all of the displacements to be given are total pressures, owing to the comparison spectrum being made with the furnace in vacuum. A careful test having shown (see Table II) that the furnace in vacuum and at atmospheric pressure shows a displacement of the lines proportional to that for higher pressures, the shifts may be compared with those for the same difference of pressure with the arc, which was usually operated at atmospheric pressure for the comparison spectrum.

IRON

In Table I the displacements are given in Ångström units for a number of iron lines in the blue region. These are all reversed by the furnace and were as a rule very favorable for close measurement. The furnace spectra at 8, 16, and 24 atmospheres are the regular reversed emission lines. At 12 atmospheres, one plate in absorption was measured and also one in which the iron lines were narrow and unreversed in a photograph of the titanium spectrum. The last column gives the displacements found by Gale and Adams for the arc with 8 atmospheres difference in pressure. The wave-lengths are on the Rowland scale.

It is seen from Table I that the displacements of all the lines, with the exception of those marked *, are of the same order of magnitude for the furnace at any given pressure. The mean shift per atmosphere for these eight lines is also nearly the same except

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 58; *Astrophysical Journal*, **35**, 10, 1912.

for the two plates at 12 atmospheres, where the rather wide absorption lines of the one and the unreversed lines of the other made measurements difficult.

TABLE I

PRESSURE DISPLACEMENTS FOR IRON

λ 4250–λ 4462

λ	8 Atm. 4 Plates	12 Atm. (Absorption) 1 Plate	12 Atm. (Unreversed) 1 Plate	16 Atm. 2 Plates	24 Atm. 1 Plate	8 Atm. Arc
4250.045	0.037	0.062	.....	0.073	0.116	0.022
4271.934	0.039	0.054	0.053	0.074	0.102	0.022
4294.301	0.036	0.064	.....	0.076	0.113	0.030
4308.081	0.040	0.055	0.055	0.081	0.116	0.021
4325.939	0.038	0.065	0.053	0.080	0.121	0.020
*4376.107	0.020	0.028	0.029	0.039	0.052	0.018
4383.720	0.040	0.063	0.056	0.080	0.119	0.027
4404.927	0.041	0.059	0.060	0.078	0.121	0.021
4415.293	0.040	0.064	.....	0.072	0.115	0.018
*4427.482	0.019	0.029	0.028	0.038	0.044	0.017
*4461.818	0.018	0.026	0.026	0.034	0.051	0.015
SUMMARY, OMITTING * LINES						
Mean displacement	0.0389	0.0607	0.0554	0.0768	0.1154	0.0226
Displacement per atmosphere	0.00486	0.00506	0.00462	0.00480	0.00481	0.00282

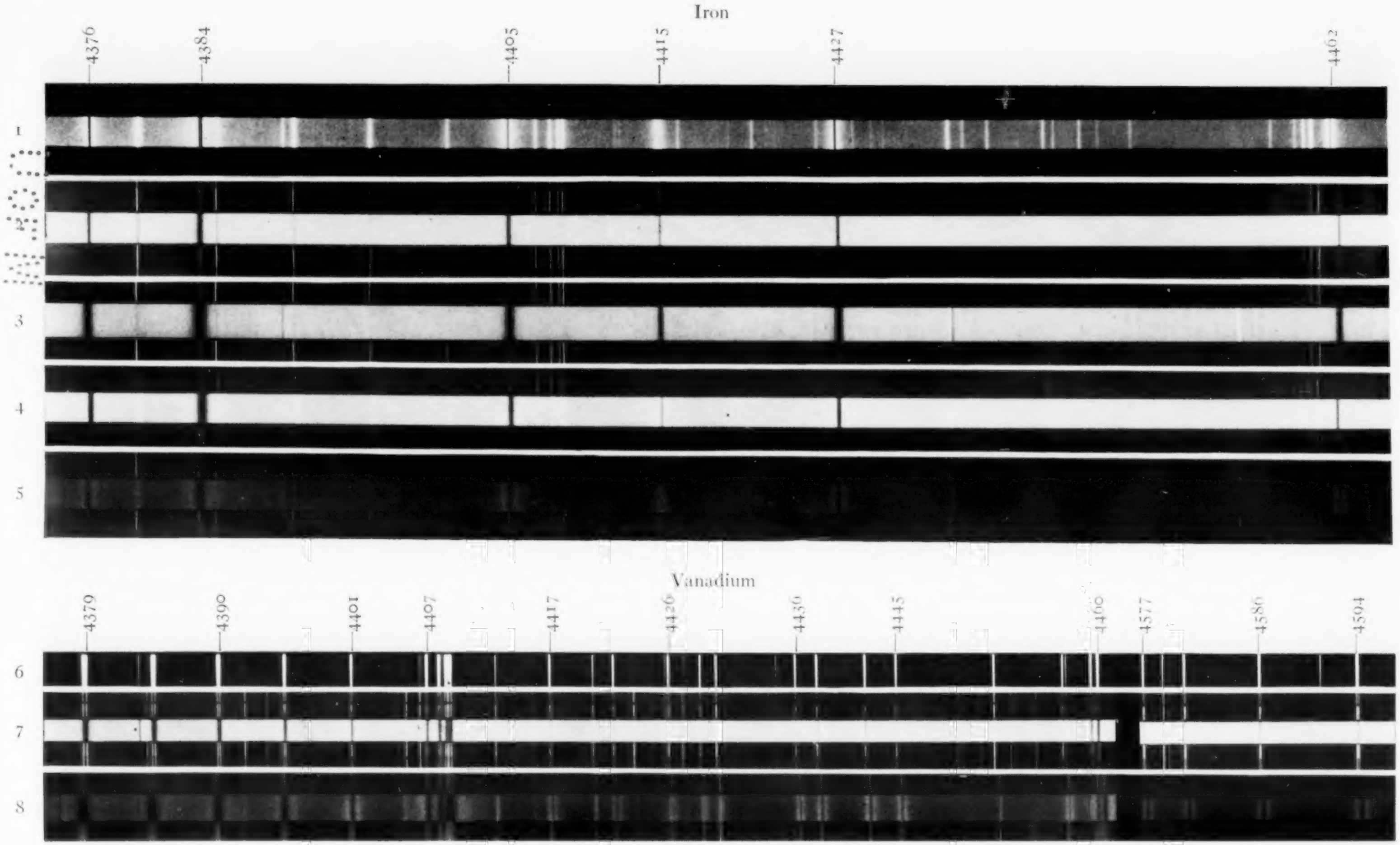
Mean furnace displacement per atmosphere 0.00483

Ratio, Arc : Furnace = 282 : 483 = 0.584

The lines $\lambda\lambda$ 4376, 4427, and 4462 are obviously in a different class as regards displacement, their shifts being about half as large as for the other lines in the list. Other lines in this region show a shift about twice as large as the unstarred lines in Table I, λ 4260.640 being the strongest of this class; but they do not reverse in the furnace and are usually so hazy for pressures above 8 atmospheres that measurements on them are of low weight and they are therefore not included in the present list.

A comparison of the furnace and arc shifts may be made most directly by means of the first and last columns of displacements. It is seen that the furnace displacements are uniformly larger than those of the arc, but that the ratio for individual lines is by no means constant. The largest deviations are for λ 4294 and for the three lines above mentioned which have small furnace displace-

PLATE XI



Effect of Pressure upon Electric Furnace Spectra

1. 8 atmospheres
2. 8 atmospheres
3. 12 atmospheres (absorption)
4. 16 atmospheres
5. 24 atmospheres
6. Arc
7. 8 atmospheres
8. 16 atmospheres

ments. The reality of this difference is not altogether certain. These four lines are given at low temperatures and so are relatively strong and well reversed in the furnace spectrum. In the arc they reverse with difficulty, if at all, so that the matter hinges on whether a definitive comparison can be made between a reversed and an unreversed line when the displacement is small and is attended by photographic differences owing to the spectra being photographed on different plates. Duffield,[1] who investigated the iron lines in this region for pressures from 5 to 100 atmospheres, obtained very irregular displacements for the three starred lines of Table I, but they have in general decidedly smaller shifts than the other lines in this table. λ 4294 was also found by Duffield to show variable shifts at different pressures, but usually gave values close to those found by him for the unstarred lines of Table I. The measurements of Humphreys[2] for 41 atmospheres, a pressure which in some respects should be more favorable for lines of this type, give a close relative agreement with the furnace displacements, λ 4294 having a shift of the same order as those measured by Humphreys for the unstarred lines of Table I, while $\lambda\lambda$ 4376, 4427, and 4462 have a mean shift per atmosphere of 0.00122, the mean value given by the furnace for 8, 16, and 24 atmospheres being 0.00225. Thus, if we allow for the character of the lines in the two sources, the lack of agreement in the measured displacements for furnace and arc may not be great enough to indicate a real relative difference.

Plate XI reproduces the iron spectrum from λ 4376 to λ 4462, showing two spectra at 8 atmospheres having different intensities for the continuous ground, an absorption spectrum at 12 atmospheres and emission spectra at 16 and 24 atmospheres. The relatively small displacements of the starred lines of Table I may readily be seen.

A large number of photographs have been taken for the region λ 5300 to λ 5500, as the strong lines in this region are especially favorable for examining the characteristics of furnace displacements. Eight lines occur in this region which are of about equal intensity and show pressure displacements of nearly the same magnitude.

[1] *Philosophical Transactions*, A **208**, 111, 1908.

[2] *Astrophysical Journal*, **26**, 18, 1907.

They reverse readily in the furnace at moderate temperatures, the width of reversal increasing progressively toward the violet. This group of lines has been studied at successive steps of 4 atmospheres up to 24 atmospheres, and also for the possible effect upon displacement of variations in temperature and other conditions of the furnace. The displacement values for various pressures are given in Table II.

Table II shows a maximum variation in the shift per atmosphere of less than 10 per cent for those conditions which may be regarded as standard, namely emission spectra in air at pressures of 4, 8, 16, and 24 atmospheres. The large values given by one plate for 12 atmospheres in absorption are of doubtful weight, owing to the width of the lines. Absorption spectra at 8 and 16 atmospheres with fairly narrow lines gave displacements close to the general mean. The large shifts measured for two plates in carbon dioxide at 8 atmospheres may be real and will be considered later in the discussion. The number and quality of the plates at disposal leave little question that there is a regular increase of displacement with pressure through this range of moderate pressures. The material thus supplements the data from arc investigations, in which as a rule many irregular values have appeared at pressures under 20 atmospheres, and in which the proportionality of displacement to pressure in this range was somewhat doubtful.

The measurements for one atmosphere require explanation, since the probable error is large in proportion to the displacement measured. The furnace was operated in a partial vacuum for the comparison and then at about atmospheric pressure, the interval being regulated by a mercury manometer for which the difference in level was kept equal to the barometric height. Three good plates having narrowly reversed lines were measured in each direction. Single determinations ranged from 0.002 to 0.008, the extreme limits being rare. As the eight lines show displacements of the same magnitude, each plate thus furnished 16 determinations of the interval in question, giving a total of 48 measurements to make up the final mean of 0.00525 for a pressure of one atmosphere. It is believed that fairly high weight can be given this value of the shift for this difference in pressure. It shows that the displace-

TABLE II

PRESSURE DISPLACEMENTS FOR IRON

λ 5328–λ 5456

λ	1 Atm. 3 Plates	4 Atm. 3 Plates	8 Atm. 3 Plates	8 Atm. (CO_2) 2 Plates	8 Atm. (Absorption) 1 Plate	12 Atm. 2 Plates	12 Atm. (Absorption) 1 Plate	16 Atm. 2 Plates	16 Atm. (Absorption) 1 Plate	20 Atm. 2 Plates	24 Atm. 2 Plates	8 Atm. Arc
5328.236	0.006	0.021	0.043	0.047	0.044	.....	.....	0.080	.....	0.097	0.124	0.029
5371.734	0.006	0.020	0.041	0.045	0.039	0.058	.....	0.079	0.091	0.109	0.121	0.029
5397.344	0.005	0.021	0.042	0.047	0.042	0.065	0.068	0.080	0.087	0.107	0.137	0.029
5405.989	0.006	0.022	0.041	0.043	0.035	0.059	0.069	0.075	0.080	0.094	0.102	0.027
5429.911	0.005	0.021	0.044	0.049	0.044	0.064	0.076	0.083	0.089	0.104	0.126	0.029
5434.740	0.004	0.019	0.036	0.042	0.036	0.053	0.070	0.074	0.073	0.093	0.115	0.027
5447.130	0.005	0.023	0.047	0.050	0.047	0.063	0.069	0.074	0.081	0.106	0.124	0.031
5455.834	0.005	0.020	0.040	0.042	0.039	0.058	0.066	0.071	0.079	0.099	0.106	0.028
Mean displacement	0.00525	0.0210	0.0418	0.0456	0.0407	0.0600	0.0697	0.0770	0.0829	0.101	0.122	0.0286
Displacement per atmosphere	0.00525	0.00525	0.00522	0.00570	0.00509	0.00500	0.00581	0.00481	0.00518	0.00505	0.00508	0.00357

Mean furnace displacement per atmosphere, 0.00522

Ratio, Arc: Furnace = 357 : 522 = 0.684

ments produced by any pressure as referred to the furnace in vacuum may be fairly compared with arc measurements, for which the pressure is usually taken as the excess above one atmosphere.

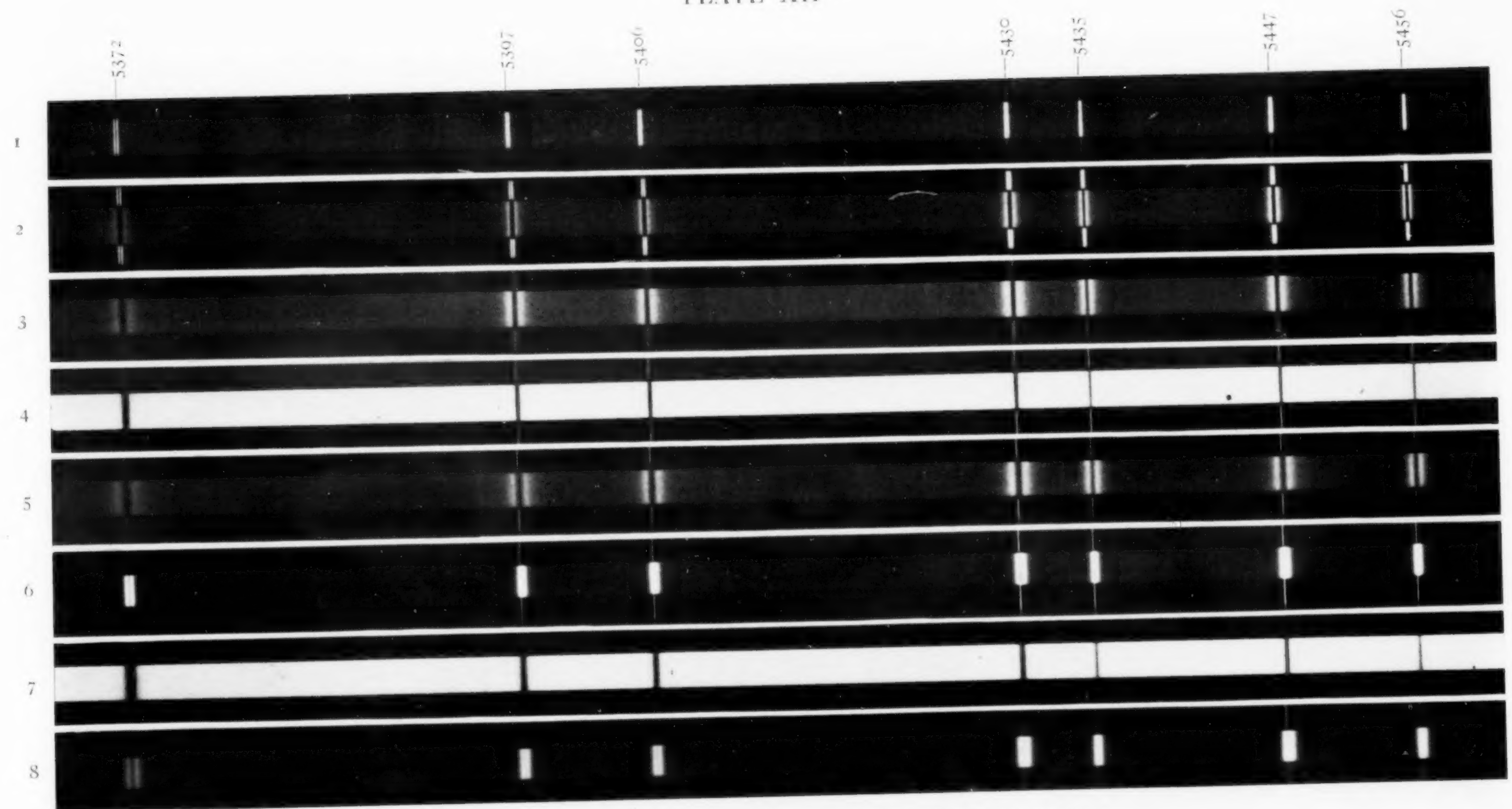
The arc displacements for 8 atmospheres as measured by Gale and Adams are given in the last column of Table II. There is a close agreement among the individual values as for the furnace. The difference between the mean shifts per atmosphere for the two sources is not so large as for the lines given in Table I, but the different appearance of the lines in arc and furnace for this region makes them more difficult to compare with accuracy. The lines of Table II are usually unreversed in the arc at moderate pressures, only λ 5328 and λ 5371 sometimes showing slight reversal. In the furnace the fact that they are low-temperature lines and are given by the vapor near the ends of the tube permits them to be clearly reversed. Another set of pressure-arc measurements for the lines of Table II is given by Humphreys.[1] His measurements for the eight lines under a pressure of 41 atmospheres gave a mean shift per atmosphere of 0.0023, or less than one-half of the mean furnace displacement. If we take the mean of Gale and Adams' and of Humphreys' values for the shift per atmosphere in the arc, it comes out 0.00293, giving a ratio of arc to furnace displacements of 0.561.

The strong lines $\lambda\lambda$ 5497.735, 5501.683, and 5507.000, are usually unreversed in the furnace, and were not so favorable for accurate measurement as the lines given in Table II. Such measures as have been made indicate that the displacements are of the same order of magnitude as those recorded for the neighboring lines.

Plate XII reproduces the lines of Table II, with the exception of λ 5328. Variations of the pressure effect are shown ranging from the slight lack of continuity at one atmosphere as compared to vacuum to the large displacements at 24 atmospheres. In all of them, the progressively increasing width of the reversal toward the violet is evident. For 8 atmospheres, both emission and absorption spectra are shown. For 16 atmospheres, two emission spectra with quite different degrees of reversal and an absorption spectrum are given. The spectrum reproduced for 24 atmospheres

[1] *Loc. cit.*

PLATE XII



Effect of Pressure upon the Electric Furnace Spectrum of Iron

1. 1 atmosphere
2. 4 atmospheres
3. 8 atmospheres
4. 8 atmospheres (absorption)
5. 16 atmospheres
6. 16 atmospheres
7. 16 atmospheres (absorption)
8. 24 atmospheres

shows for most of the lines only the beginning of reversal. Another plate was obtained at this pressure with rather wide reversals.

TITANIUM

The titanium furnace spectrum was photographed for the region λ 4200 to λ 4600, in which two groups aggregating 20 lines were strong enough to measure up to 16 atmospheres. These lines are not reversed by the furnace at the temperatures employed. A good agreement appeared for sets of measurements by different observers, although the lines were not as satisfactory for measurement as if they had been reversed. An absorption spectrum at 8 atmospheres gave displacements agreeing closely with the values for emission spectra. The measurements are presented in Table III, the arc displacements found by Gale and Adams for 8 atmospheres being given in the last column. The mean furnace shift per atmosphere is weighted on account of the small number of values for 12 atmospheres.

Considering the character of the lines there is a good agreement between the displacements at 8 atmospheres for emission and absorption and also between the shifts per atmosphere at 8 and 16 atmospheres. The ratio of mean arc and furnace displacements is almost the same as for the iron lines of Table I. The arc displacements for the 11 lines beginning with 4512.906 are consistently somewhat higher than for the first 9 lines in the list, while the furnace displacements are of the same magnitude throughout.

As in the case of the iron spectrum, only the best lines are measured in this region. A much larger number can be obtained with varying degrees of accuracy, the precision in most cases becoming much less at higher pressures.

VANADIUM

Recent work by Rossi[1] has furnished measurements for the displacements of the stronger vanadium lines from λ 4000 to λ 4600 as given by the arc at pressures of 15, 30, 50 and 100 atmospheres. The writer has taken a series of ten furnace plates for the same region at pressures of 8 and 16 atmospheres. Compressed air was used, with metallic vanadium in the furnace tube. On the better

[1] *Astrophysical Journal*, **34**, 21, 1911.

photographs the lines were in almost all cases reversed, the comparison lines also being frequently reversed, so that close measurements were possible.

TABLE III

PRESSURE DISPLACEMENTS FOR TITANIUM

λ	8 Atm. 2 Plates	8 Atm. (Absorption) 1 Plate	12 Atm. 1 Plate	16 Atm. 2 Plates	8 Atm. Arc
4286.168....	0.045	0.049	.....	0.087	0.021
4287.566....	0.040	0.048	.....	0.099	0.024
4289.237....	0.050	0.049	.....	0.075	0.025
4291.114....	0.049	0.042	.....	0.091	0.022
4295.914....	0.046	0.054	.....	0.094	0.022
4298.828....	0.045	0.054	.....	0.095	0.025
4300.732....	0.046	0.046	0.081	0.099	0.021
4301.158....	0.048	0.050	0.076	0.088	0.024
4306.078....	0.044	0.048	0.073	0.091	0.024
4512.906....	0.047	0.043	.....	0.088	0.029
4518.198....	0.046	0.049	.....	0.099	0.029
4522.974....	0.047	0.045	.....	0.099	0.031
4527.490....	0.044	0.056	.....	0.100	0.029
4533.419....	0.043	0.047	0.077	0.097	0.031
4534.953....	0.047	0.052	0.074	0.094	0.034
4535.741....	0.043	0.046	0.082	0.102	0.029
4544.864....	0.048	0.050	.....	0.094	0.031
4548.938....	0.045	0.044	.....	0.099	0.031
4552.632....	0.045	0.046	.....	0.097	0.029
4555.662....	0.046	0.049	.....	0.090	0.029
Mean displacement..	0.0457	0.0483	0.0772	0.0939	0.0270
Displacement per atmosphere......	0.00571	0.00604	0.00643	0.00587	0.00338

Mean furnace displacement per atmosphere, 0.00592
Ratio, Arc : Furnace = 338 : 592 = 0.571

Table IV gives the furnace displacements for vanadium, the arc displacements measured by Rossi for 15 atmospheres being given in the last column. The values in the third column, for unreversed lines at 8 atmospheres, were obtained from a plate made for the iron spectrum, but containing the stronger vanadium lines narrow and bright from impurities in the iron.

From Table IV it is seen that the displacements per atmosphere at 8 and 16 atmospheres agree within 10 per cent. As the reversals at 16 atmospheres are rather wide, a difference of this magnitude may fairly be ascribed to errors of measurement and the propor-

TABLE IV

PRESSURE DISPLACEMENTS FOR VANADIUM

λ	8 Atm.	8 Atm. (Unreversed)	16 Atm.	15 Atm. Arc
4090.728....	0.070	.....	.....	0.071
4092.821....	0.040	.....	.....	.....
4095.633....	0.045	.....	.....	0.061
4099.941....	0.040	.....	.....	0.049
4102.321....	0.060	.....	.....	0.047
4105.318....	0.047	.....	.....	.....
4109.905....	0.040	.....	.....	0.052
4111.940....	0.046	.....	.....	0.043
4115.330....	0.038	.....	.....	0.043
4116.634....	0.053	.....	.....	0.042
4123.539....	0.040	.....	.....	0.050
4128.251....	0.047	.....	.....	0.046
4132.100....	0.043	.....	.....	0.049
4134.589....	0.046	.....	.....	0.044
*4179.542....	0.016	.....	.....	.....
4182.755....	0.041	.....	.....	.....
*4330.189....	0.023	.....	0.039	0.042
*4332.988....	0.018	.....	0.034	0.041
*4341.167....	0.020	.....	0.045	0.052
*4353.040....	0.023	.....	0.039	0.040
4379.396....	0.042	0.049	0.086	0.046
4384.873....	0.042	0.040	0.087	0.046
4390.149....	0.048	0.044	0.085	0.043
4395.413....	0.040	0.046	0.084	0.047
4400.738....	0.035	0.044	0.091	0.047
4406.810....	0.037	0.042	0.081	.....
4407.810....	0.040	0.047	0.078	.....
4408.364....	0.040	0.040	.....	.....
4408.683....	0.057	0.047	.....	.....
4416.636....	0.035	0.042	0.084	0.043
4421.733....	0.044	0.037	0.096	0.046
4426.201....	0.044	.....	0.075	0.044
4428.711....	0.034	.....	0.065	0.046
4429.958....	0.044	.....	.....	0.047
4436.313....	0.034	.....	0.062	0.049
4438.006....	0.035	0.031	0.077	0.043
4441.881....	0.033	0.036	0.084	0.050
4444.566....	0.035	0.037	0.074	0.049
4457.600....	0.038	.....	0.054	.....
4459.922....	0.036	0.033	0.059	.....
4460.389....	0.041	0.035	0.080	.....
*4577.356....	0.019	.....	0.038	0.044
*4580.590....	0.018	.....	0.034	0.042
*4586.552....	0.020	.....	0.033	.....
*4594.297....	0.021	.....	0.036	0.041
SUMMARY, OMITTING * LINES				
Mean displacement.....	0.0427	0.0406	0.0779	0.0478
Displacement per atmosphere......	0.00534	0.00507	0.00487	0.00319

TABLE IV—*Continued*

λ	8 Atm.	8 Atm. (Unreversed)	16 Atm.	15 Atm. Arc
Mean displacement of lines also in arc. .	0.0428	0.0406	0.0808	....
Displacement per atmosphere of lines also in arc.	0.00535	0.00507	0.00505	....

Mean furnace displacement per atmosphere, 0.00509
Mean furnace displacement per atmosphere for lines also in arc, 0.00516
Ratio, Arc : Furnace = 319 : 516 = 0.618

tional increase of the displacements in general is in harmony with the results for iron and titanium.

The ratio of the mean displacements per atmosphere for lines common to the furnace list and to Rossi's list for the arc is close to that found in Tables I and III. The last two columns of Table IV show the relative displacements in furnace and arc for nearly equal pressures. Nine furnace lines which have shifts much smaller than the average are starred and are not included in the averages at the end of the table. For the seven lines of this set which were measured by Rossi, there appears to be a distinct relative difference as compared to the unstarred lines. At 16 atmospheres the furnace displacements of the starred lines are close to those of the arc for 15 atmospheres while the displacements for the other lines approach a 2 : 1 ratio. These lines were measured on several good furnace plates and there can be no doubt of their large difference from the unstarred lines. So far as can be judged from the reproductions of Rossi's spectra, the starred lines in the arc spectra are comparable in quality with the others in his table. It is to be noted, however, that Rossi's measurements for 30 atmospheres, which gave the lines distinctly reversed in the arc, show consistently smaller values for the starred lines than for the others. Until a more direct comparison of furnace and arc photographs is possible, there is some question as to the certainty of a large relative difference for these lines.

Vanadium spectra at 8 and 16 atmospheres, accompanied by an

arc spectrum taken at atmospheric pressure, are reproduced in Plate XI. The four lines from λ 4577 to λ 4594 appear at the right, showing their displacements relative to those of the lines near λ 4400. The two parts of the spectrum at 8 atmospheres were enlarged from the same negative, so that photographic differences are eliminated.

EFFECT UPON DISPLACEMENT OF VARIATION IN FURNACE CONDITIONS

Since many modifications are possible in the arrangement and operation of the furnace, it seemed worth while to see what differences, if any, changes in certain variables might make in the pressure displacements. The region of spectrum selected for these experiments consists of the iron lines whose measurements for different pressures are given in Table II, with the addition of λ 5269.723 on some of the photographs. The lines of this group have the advantages of giving fairly large displacements, all of the same order of magnitude, so that the mean can be used to determine the effect of any special condition, and of appearing usually in reversal, which in the case of low temperature lines greatly increases the accuracy of measurement. The various modifications tried will be considered in turn.

1. *Temperature difference.*—A variation in pressure displacement inversely as the absolute temperature of the source would be of the proper order of magnitude to account for the difference observed in furnace and arc displacements. It has been possible to test this point with the furnace in such a way that a relation of this kind should have shown itself, but the results have failed to reveal a dependence of displacement upon temperature.

In these experiments a definitive test required a pressure high enough to give a large displacement and also a temperature difference as great as possible, both conditions acting against obtaining lines of the best quality for a close comparison. Pressures of 12, 16, and 20 atmospheres were used. At each pressure, a temperature was taken as low as would give clearly defined lines and then as high as could be employed. It was not possible to go to the upper limit of the furnace temperature, as wide reversals were given, and if the exposures were made long enough to narrow the reversals only

temperatures up to a certain limit could be used without generating large quantities of white vapor which cut off the light.

Little confidence could be placed in comparative measurements for the extreme low and high temperatures on account of the diffuseness of the lines at the pressures employed. To obtain good lines for measurement, the furnace was always operated at moderate temperatures (not above 2400° C.). The method adopted for the temperature comparison was to make exposures at the same pressure for low and high temperatures on the same plate, placing one outside of the other by means of the occulting device above the slit, and making vacuum exposures before and after to test for instrumental disturbance during the experiment.

Twelve plates were taken by this method for the iron lines from λ 5300–λ 5500 and from λ 4200–λ 4500. Various temperature intervals were taken, usually those for which the pyrometer gave differences of about 500° C. The actual difference was probably greater than this on account of the readings being affected by the cloudy condition of the furnace interior at the high temperatures. Very good plates were obtained at 12 atmospheres with lines reversed in each photograph taken with a temperature difference of about 300° C. The reversals appeared to be perfectly continuous in the two spectra side by side. Larger temperature intervals gave the low temperature lines unreversed, and the maximum difference should have been given for 20 atmospheres with a temperature interval of at least 500°. This gave an absolute displacement of about 0.1 Å for both lines, and no difference in position could be detected between bright low temperature lines and the same lines reversed at high temperature. A difference in displacement inversely proportional to the absolute temperature would amount to about 20 per cent under these conditions and although the quality of the lines makes one hesitate to say that there is certainly no difference, it can be said that a difference of this magnitude should have been perceptible in a visual comparison made in this way. Higher pressures were tried, up to 30 atmospheres, but difficulties attendant on the increased pressure prevented the obtaining of photographs satisfactory for comparison at both high and low temperatures.

Evidence offered by the structure of reversed lines bears on the effect of temperature difference. All of the lines whose measurements are given in this paper, when reversed at all, show reversals nearly if not quite symmetrical up to the highest pressures observed, 24 atmospheres in the case of the iron lines. An increased displacement for the low temperature line given by the cooler parts of the furnace tube should make the line as a whole unsymmetrically reversed, the portion to the violet of the absorption line being the wider. Lines having this appearance are rare in any source, the arc usually giving strong widening to the red when lines reverse unsymmetrically, while, for the lines considered in this paper, the symmetry of the arc reversals agrees with those shown by the furnace. A condition which is conceivable but highly improbable may be mentioned. If the emission line widened under pressure unsymmetrically toward the red and if at the same time the absorption line had a larger displacement owing to the lower temperature of the vapor producing it, the widening of the emission line and the increased displacement of the absorption line might keep pace and preserve the appearance of symmetrical reversal. There is no reason to believe that this actually takes place. Such lines when unreversed under pressure should show strong widening toward the red. The iron lines of Table II have been obtained in the furnace unreversed at several pressures. They also appear usually unreversed in the arc under pressure and much widened when iron terminals are used, but this widening remains nearly symmetrical both in furnace and arc.

If a decrease of displacement with increasing temperature were found really to exist, the widening of the lines, which seems to accompany increased pressure in all sources which have been observed, would be expected to remain, and we should have the condition in solar and stellar spectra that lines widened but not distinctly displaced might indicate high pressures which produced little or no displacement by reason of the high celestial temperatures involved. The evidence presented by the furnace experiments, however, is against a dependence of the pressure displacement on the temperature of the source.

2. *Effect of different compressed gases.*—It was noted in the dis-

cussion of Table II, that two good plates for the furnace in carbon dioxide at 8 atmospheres gave consistently larger displacements than were observed for compressed air, the difference of the means amounting to about 10 per cent. This difference is not certainly beyond possible errors of measurement, but the measurements by different observers agreed very closely and the difference is larger than was obtained between photographs of similar quality for any other conditions of the furnace. Photographs of poorer quality for the iron lines of Table I and the titanium lines of Table III, each at 8 atmospheres in CO_2, failed to show a decided difference from corresponding photographs for air. Higher pressures with carbon dioxide gave poor results on account of the large amount of white oxide which was generated.

The possibility of carbon dioxide giving larger pressure displacements than air on account of its higher dielectric constant was discussed in my preliminary paper.[1] The present results show that this can have no important bearing on the difference between furnace and arc displacements, since the greater part of the furnace work has been done with air. Rossi[2] has recently tested this question for the arc by obtaining the displacements of a number of iron lines in air and in carbon dioxide at 15, 30, and 50 atmospheres. The mean displacements for the two gases agreed closely.

It is worthy of note in this connection that, judging from my experiments with the furnace, the carbon dioxide is probably largely turned to carbon monoxide before it reaches the region where maximum radiation is taking place, and the same is probably true to a certain extent for the arc. As the dielectric constant of carbon monoxide is but slightly greater than that of air, being much less than for carbon dioxide, but little difference in displacement is to be expected through this agency. The furnace should, however, be more sensitive than the arc to any influence which the compressed gas can exert, since such a gas is thoroughly mixed with the metallic vapor and brought to the same temperature.

3. *Low vapor-density.*—Table V gives a summary of the displacements for the furnace at 8 atmospheres under various conditions,

[1] *Loc. cit.*

[2] *Philosophical Magazine* (6), **21**, 499, 1911.

the furnace tube being used without jacket in order to eliminate any effect due to vapors given off by the jacketing materials in the presence of oxygen. Compressed air was used throughout. On account of the tube rapidly becoming thinner when fully exposed to the air, some difficulty was found in keeping the temperature approximately constant, which affected the clearness of the reversals. The plates were thus not so satisfactory for measurement as those for which the jacket was used, and the deviations of small size from the values given in Table II are probably to be ascribed to this cause. From one to four good plates were measured for each condition summarized in Table V.

TABLE V

PRESSURE DISPLACEMENTS FOR IRON AT 8 ATMOSPHERES UNDER VARYING CONDITIONS OF THE FURNACE

λ	Tube 20 or 25 cm Long				5 or 6.4 cm Tube
	From Table II	Small Amount of *Fe*	*Fe* with *Ca* and *NaCl*	Small Amount of *Fe* with *Ca* and *NaCl*	
5269.723....	.....	0.044	0.036	0.038	0.037
5328.236....	0.043	0.043	0.044	0.041	0.039
5371.734....	0.041	0.043	0.040	0.041	0.038
5397.344....	0.042	0.044	0.040	0.045	0.045
5405.989....	0.041	0.043	0.037	0.041	0.039
5429.911....	0.044	0.044	0.040	0.040	0.042
5434.740....	0.036	0.044	0.033	0.037	0.039
5447.130....	0.047	0.042	0.038	0.042	0.038
5455.834....	0.040	0.042	0.035	.....	0.039
Mean.......	0.0418	0.0432	0.0381	0.0406	0.0396

Plates taken without the jacket for the regular size of tubes and usual amount of iron gave means very close to those of Table II; so the first column of displacements is taken directly from Table II and used for comparison with the values for the special conditions in which no jacket was employed.

A very little iron (about 0.05 gram as compared with 2 grams or more generally used) gave lines unreversed, but of good quality for measurement. The displacements for the several lines agreed very closely as is seen in the third column of Table V, the mean being close to the general mean of Table II. The furnace thus

confirms the conclusion that has been drawn by a number of observers of the arc under pressure that displacement is not dependent on the quantity of the metallic vapor present.

4. *Effect of foreign vapors.*—In a long column of vapor such as that given by the furnace tube, irregular refraction effects are possible, which may under certain conditions give a displacement of the lines to the red. In the usual operation of the furnace, with the jacket about the tube, the spectrum showed that a considerable amount of calcium and sodium was present, presumably given off by the carborundum and graphite, and in order to see if the displacement was affected thereby, an attempt was made to increase the effect by introducing a large quantity of metallic calcium and sodium chloride with the iron. To insure maximum effect during the pressure exposure, these were put into the tube, by removing the window-holder, after the first comparison exposure in vacuum had been made. A brilliant banded spectrum from the calcium, together with very widely reversed D lines, attested the presence of a dense vapor from these substances, especially in the earlier stages of the furnace run. Some of the photographs under these conditions were rather difficult to measure, the reversals appearing as if an unsteady distribution of the vapor had existed during the exposure, which may have been due to disturbances other than refraction. I am not prepared to say that anomalous dispersion does not enter in some degree when a mixture of this sort is present in the tube, but such effect as there is on the displacements is in the direction of lower values; so that the generally high values of the furnace as compared to the arc are not explained by an influence of this sort. Tubes with 25 cm heated between the contact blocks were used for some of these tests. The mean displacements obtained are given in the fourth and fifth columns of Table V, the latter column giving the results when a very little iron was used with the calcium and salt. The deviation of the means from the value in column two, in view of the character of the lines, is not large enough to indicate a real effect on the displacement.

5. *The use of short tubes.*—The method of using tubes of about one-fourth the regular length was described on p. 186. If the length of the column of vapor were an essential factor in determining the

displacement, a decided difference should have appeared for these tubes. The vapor-density was kept closely comparable with that for the long tubes by using a quantity of iron proportional to the length of the tube. The results are given in the final column of Table V. A difference of only 5 per cent appears between this mean and that in the second column, so that the length of the tube can be regarded as without decided effect on the displacement.

COMPARISON WITH THE ZEEMAN EFFECT

A comparison of the pressure displacements with the separations produced by a magnetic field for the lines considered in the present paper offers little evidence in support of a close connection between the two phenomena.

The magnetic separations for the iron and titanium lines have been published by the writer[1] and those for vanadium by Mr. Babcock.[2]

The iron lines of Table I show triplet separation in the magnetic field with the exception of $\lambda\lambda$ 4251 and 4294 which are complex. The remaining lines, including λ 4415 which may have more than three components, have the following values of the separation divided by the square of the wave-length for a field of 16,000 gausses:

λ	$\Delta\lambda/\lambda^2$	λ	$\Delta\lambda/\lambda^2$
4271.934	1.868	4404.927	1.720
4308.081	1.724	4415.293	1.734
4325.939	1.309	4427.482	2.194
4376.107	2.214	4461.818	2.185
4383.720	1.727		

These measurements for the separations are all of high weight. $\lambda\lambda$ 4376, 4427, and 4462 are seen to have magnetic separations of equal magnitude, this separation being distinctly larger than those of the remaining triplets in the list. Their pressure displacements in the furnace, however, are about half as large as those of the other

[1] *Papers from the Mount Wilson Solar Observatory*, Vol. II, Pt. 1; *Carnegie Institution Publication* No. 153, 1912.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 55; *Astrophysical Journal*, **34**, 209, 1911.

lines. The relative effects of pressure and of the magnetic field are thus opposite for the two groups of triplets in this list.

The iron lines of Table II, which agree among themselves as to pressure displacement, show a variety of magnetic separations, all of them complex with the exception of λ 5434.740, which is unaffected by the magnetic field. There is therefore no clear basis for comparison of the two effects. The case is similar for the titanium lines of Table III, the displacements being of about equal magnitude, while the magnetic separation varies from an unaffected line (λ 4295.914) to those having from 8 to 12 components.

The vanadium lines of Table IV show two groups of four lines each (λ 4330–λ 4353 and λ 4577–λ 4594) which have about half of the average displacement. These 8 lines are all given as showing triplet separation in the magnetic field, as do 25 other lines in Table IV. The average value of $\Delta\lambda/\lambda^2$ for 20,000 gausses is 1.81 for the 8 small-shift lines and 2.55 for the 25 lines having larger displacements. The effects of pressure and of the magnetic field are thus in the same direction for these groups.

The data here given do not materially alter the general situation as to the relation of the pressure and Zeeman effects, since the writer has shown[1] that no close correspondence exists between the effects for individual lines or even small groups, a general agreement as to relative magnitude becoming apparent only when the means of large numbers of lines are considered.

THE RELATION OF DISPLACEMENT TO WAVE-LENGTH

One or two points concerning the iron lines of Tables I and II may be referred to here, though the number of lines is small for a discussion of the relation to the wave-length. The average displacement per atmosphere of the lines from λ 5300 to λ 5500 is but little larger than for the lines showing the larger shifts in the region λ 4200 to λ 4500. The displacements of the three lines in Table I showing small shifts, however, are related to the displacements of the lines in Table II very nearly as the third power of the wave-length, a relation which was found by Gale and Adams[2] to hold for

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 46; *Astrophysical Journal*, **31**, 433, 1910.

[2] *Loc. cit.*

the mean displacements of iron lines in the arc through a long range of the spectrum. The ratio of the cubes of the mean wave-lengths for the two regions would require a displacement of 0.023 Å at 8 atmospheres for $\lambda\lambda$ 4376, 4427, and 4462, a value slightly higher than that given for these lines in Table I.

The chief significance of this result, in the writer's opinion, lies in the fact that the three blue lines are very similar to the lines of Table II in their response to temperature excitation of the furnace. At low temperatures they are relatively strong as compared to the other lines in Table I, and the similarity holds for their appearance in the arc, where these low temperature lines are usually sharp and reverse with difficulty. The unstarred lines of Table I are less comparable in general behavior with those of Table II, since they are strong under all conditions and are susceptible to pronounced widening and reversal in the arc. The lack of distinct change in the displacements of such lines with the wave-length seems less significant than the approximate third-power variation for lines showing the same sort of response to temperature.

THE DIFFERENCE OF FURNACE AND ARC DISPLACEMENTS CONSIDERED IN CONNECTION WITH WIDENING PHENOMENA

It is apparent in Tables I to IV that there is a consistent difference, usually of about 80 per cent, between the displacements per atmosphere of groups of lines given by the furnace and arc which as a rule are fully comparable as to accuracy of measurement in the two sets of spectra. Naturally there are individual cases, some of which have been noted, where the quality of the lines for measurement is better in one source than in the other, but this can scarcely exert any effect on the general result. The precautions taken to make instrumental conditions as much alike as possible for furnace and arc observations made in this laboratory have been described. As a guard against personal differences in measurement, Miss Lasby, who took part in the reduction of the pressure-arc photographs, has kindly measured several of the furnace plates, with the result that no systematic difference in values can be ascribed to the method of measurement. The possible influence of unsymmetrical widening has been carefully considered, but this appears to explain but little

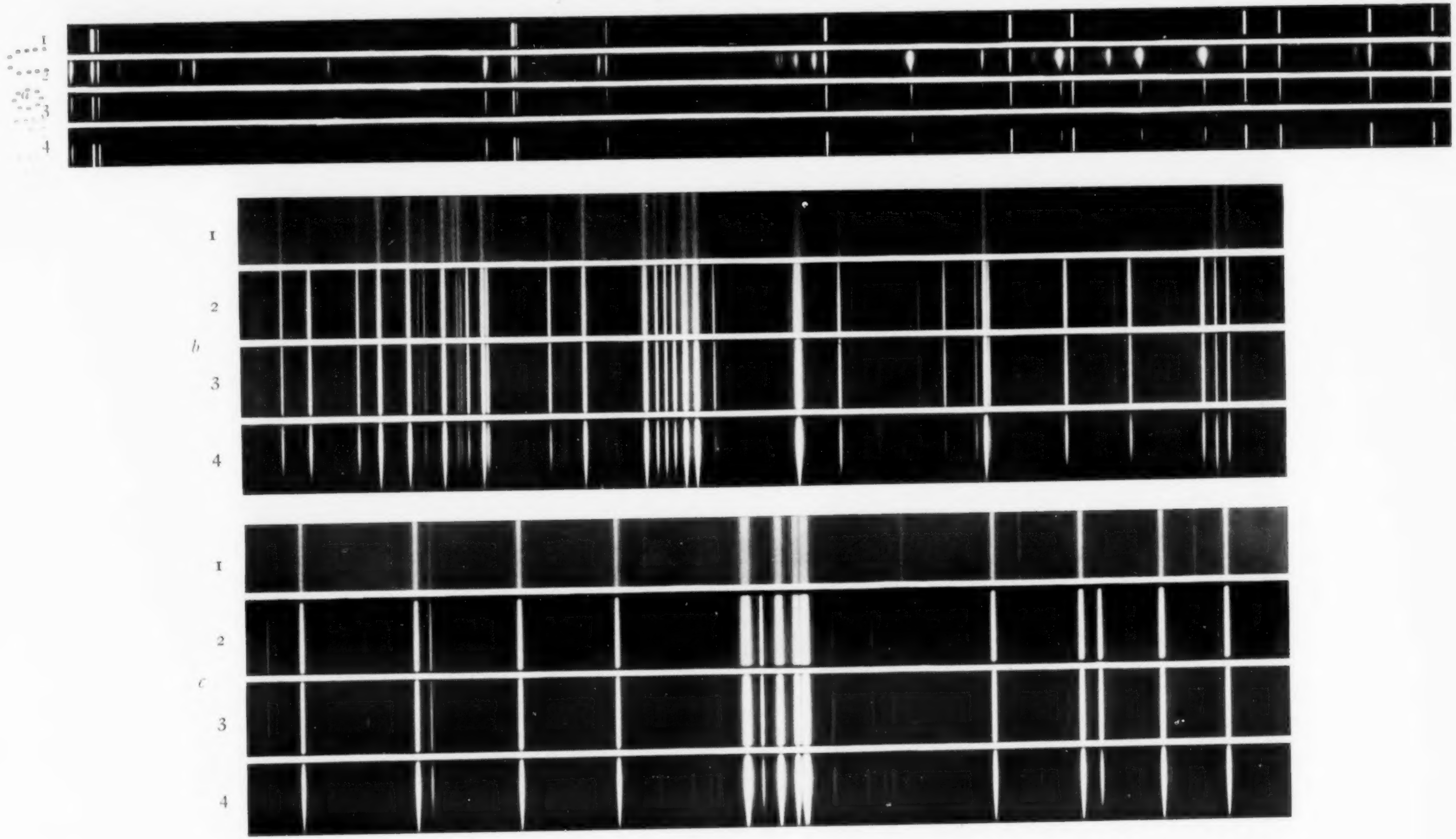
of the effect, largely because most of the lines listed here do not seem to widen unsymmetrically in any source. The reversals have occasionally been obtained very narrow compared to the total width of the line for pressures of 16 atmospheres or more (see for example λ 5371 in No. 6 of Plate XII). In such cases a widening of the reversal toward the red which could affect the measurement would be accompanied by a very pronounced dissymmetry of the line as a whole.

The various modifications of the furnace which have been tried have proved ineffective in producing a distinct difference in the mean displacement of the lines. For most of the differences between the radiation conditions of furnace and arc, however, it is difficult to bridge fully the gap between the two sources.

It is now desired to call attention to a difference in the structure of furnace and arc lines which I believe may furnish the key to their different displacements. I have always observed in furnace spectra a certain "softness" in the appearance of the lines. As compared to arc lines photographed on the same plate, the furnace lines have a more uniform intensity over their width, so that for the same width in the negative the furnace lines are less dense than those of the arc. This indicates a flatter intensity-curve for the furnace lines, a smoothing down of the central maximum, which seems to be different in character and more fundamental than a widening produced by changes in the quantity of vapor present.

The furnace, except when used for pressure experiments, has generally been operated in a partial vacuum to avoid oxidation, and even this condition, which favors the narrowness of furnace lines as compared to those given by the arc in open air, showed this relatively large width of lines in the furnace spectrum. In order to make a closer comparison of the widening in furnace and arc, a special set of photographs was made for the iron and titanium lines whose pressure displacements are studied in this paper. The furnace was excited at atmospheric pressure, the outlet valve being left open. Then a number of exposures were made on the same plate with the arc in open air for currents ranging from 2 to 20 amperes, the exposure times being graduated to make the various arc spectra of about equal intensity. A change in current seems

PLATE XIII



Furnace and Arc Spectra of Iron and Titanium

a Iron λ5270 to λ5456. b. Titanium λ4281 to λ4327. c. Titanium λ4513 to λ4556

1. Furnace at atmospheric pressure. 2. Arc, 20 amperes. 3. Arc, 10 amperes. 4. Arc, 2 amperes

Scale: a, 1 mm = 0.95 Å. b and c, 1 mm = 0.32 Å

to be the most effective means of increasing the widening of arc lines when plenty of the substance is ready to be vaporized, as when metallic terminals are used. As we cannot get at the relative quantity of vapor per unit volume in the furnace and arc under given conditions, the two sources are best made comparable by having the metal abundant in each, as was done by placing a large amount of powdered iron or titanium in the furnace tube and using as arc terminals iron rods or carbons, of which the lower held a large quantity of titanium carbide.

Plate XIII shows portions of the iron and titanium spectrum containing the lines of Tables II and III as given by the furnace at atmospheric pressure and by the arc in air at 20, 10, and 2 amperes. Width of slit and all adjustments of the spectrograph were unchanged during each series and the negative was copied on a single plate, effects of this sort being very sensitive to differences in photographic contrast. The first set of spectra shows the iron arc at 20 amperes giving about the same degree of reversal as the furnace, $\lambda\lambda$ 5269, 5328, and 5371 being reversed. None of the lines are reversed in the arc at 10 amperes or less. It is seen that the furnace lines are wider than those of the arc even for 20 amperes, while the negative shows the arc lines to be slightly the blacker. Another negative, not so favorable for reproduction, shows a furnace spectrum having lines of the same width as arc lines which are twice as black.

The lower part of Plate XIII shows the two portions of the titanium spectrum measured in Table III. The enlargements are made from the same negative, the furnace spectrum at atmospheric pressure, together with arc spectra at 20, 10, and 2 amperes, being arranged as for the iron series above. Several of the stronger lines show the beginnings of reversal in the furnace, such lines being distinctly reversed in the arc at 20 amperes, but not for 10 amperes. The greater width of the furnace lines in proportion to their density when compared to the arc lines is very distinct. The appearance of the furnace lines is approached most nearly by the arc at 20 amperes, but even then the widening conditions in the arc are not as strong as in the furnace.

The furnace was not used at atmospheric pressure for vanadium,

but the difference in structure of furnace and arc lines is shown by comparing the arc spectrum of vanadium in Plate XI with the vacuum furnace photograph immediately below it, used as comparison for that at 8 atmospheres pressure, arc and furnace exposures being on the same plate. Even in vacuum, the furnace gives broad lines, easily reversed, in contrast to the narrow, dense structure of the corresponding lines in the arc.

It would seem, therefore, that we have consistent experimental evidence of a tendency of the furnace to produce lines wider in proportion to their density than are given by the arc, at least for the moderate currents usually employed in pressure-arc work. The application to the displacement question is that *if the radiation of the furnace is such as to give lines which are wide in proportion to their density, then since widening and displacement are inseparably bound together when pressure is acting, the furnace lines, being more susceptible to the widening influence, should also respond more readily to the displacing action of pressure.* Again it must be borne in mind that this widening refers to a change in the intensity-curve for a given line, not to the general strengthening and proportional widening which results from greater vapor-density.

It is not clear why the radiation conditions of the furnace should give lines of large absolute width, and the theory of widening, so far as worked out, gives little aid in the explanation; but experiment shows the action of the furnace to be in this direction. It is evident, however, that the conditions of emission and absorption in the furnace tube will account for some features in the appearance of the lines. Reversal certainly takes place easily in the furnace for most of the lines considered in this paper. It follows that such lines when unreversed will have the peak of the emission-curve flattened to a greater or less extent by absorption. An approach to uniform density across the width of the furnace line would then result, especially as there is some variation in the condition of the vapor during the exposure time required for these large scale photographs. This relation of emission and absorption, together with a width of line approached in the arc only for high current-strength, form the distinguishing characteristics of the furnace lines.

It seems to me probable that such other apparent variations of pressure displacement in different sources as have been observed may well be based on this ability of a source to give widened lines when such widening depends upon features of the source other than vapor-density. Gale and Adams[1] obtained consistently larger mean displacements for a number of lines in the titanium spark than were given by the arc. We have again the experimental fact that lines are wider in the spark than in the arc. Gale and Adams also note that these titanium lines reverse more widely in the spark, though usually symmetrically. The decidedly larger displacements of enhanced lines given by the spark may be based on the same cause, since for such lines the widening influence of the spark discharge has a maximum effect.

The mechanism by which the furnace gives relatively wide lines must be quite different from that acting in the spark, where the widening depends upon the disruptiveness of the discharge and the lines can be made very narrow by the use of self-induction in the circuit.

According to the above hypothesis, any light-source whose radiation is such as to give widened lines should give relatively large pressure displacements. A very high-current arc should give larger displacements than an arc with low current. Also, it should be possible to vary spark displacements by gradually taking out self-induction and increasing the capacity. No systematic experiments on these points have been carried out, and in any case comparative measurements would be difficult by reason of the large difference in the character of the lines produced by very diverse conditions of the same source. For sources widely different in nature, as are the arc and the furnace, differences in radiation can exert their full effect and still lines can be obtained in the spectrum of each whose measurements are fully comparable.

SUMMARY

The leading results of this investigation are as follows:

1. Sufficient material has been collected to give measurements of fairly high weight for the displacements of certain groups of lines in the iron, titanium, and vanadium spectra.

[1] *Op. cit.*, p. 41.

2. The measured displacements of iron lines for pressures from 1 to 24 atmospheres and for titanium and vanadium lines for 8 and 16 atmospheres as compared to vacuum show a close proportionality between displacement and pressure for these ranges.

3. The pressure effect in absorption has been developed as a useful method for certain kinds of lines, giving displacements in general of the same magnitude as for emission lines.

4. Temperature differences of at least 500° C. for a pressure of 20 atmospheres have failed to show a definite variation of displacement with the temperature.

5. Variations in quantity of vapor present and in length of tube, also the addition of foreign vapors, have not appeared to affect the furnace displacements.

6. Some additional data have been secured regarding the degree of correspondence between displacement and magnetic separation.

7. A few iron lines affected similarly by temperature-changes are compared in regard to change of displacement with wave-length.

8. The furnace has in general given displacements much larger than those of the arc, and a special study has been made of the structure of furnace and arc lines which it is believed may contribute to an explanation of this difference.

I am indebted to Miss Sheldon for regular assistance in measuring the photographs, also to Miss Lasby for check measurements on several plates.

Mount Wilson Solar Observatory
February 1912

ON THE MEASUREMENTS OF THE ZEEMAN EFFECT[1]

By A. COTTON

In the *Astrophysical Journal* of December 1911 (**34**, 212), J. E. Purvis calls attention to the fact that the absolute values of the Zeeman effect for four chromium lines given by himself and by Miller, W. Hartmann, and by Babcock, are not at all in agreement. I propose to show that this disagreement arises chiefly from the measurement of the magnetic fields used, and to call the attention of physicists to the precautions which must be taken in order to render the measurements made in different laboratories comparable with one another.

Let me say first of all that Purvis utilizes Miller's measurements in accepting the value of the field as 23,850 units, given in the author's paper. But Miller had never measured directly the magnetic fields that he used. Like several other physicists, Moore, Jack, etc., he calculated the value of the fields that he used on the basis of the magnetic separation of the series lines studied by Runge and Paschen.

Now, in their beautiful pieces of work[2] these scientists had not proposed to make absolute measurements themselves. A measurement by Färber on the blue lines of zinc had led them to estimate provisionally at 23,850 units the field which they used for the study of the lines of mercury and which was afterward taken as a comparison field by several physicists.

P. Weiss and I published in 1907[3] the results of an absolute measurement of the Zeeman effect for these lines. The magnetic fields used had been measured with care by two distinct methods; the plates were measured separately by the two collaborators, care being taken to make the measurements on different parts of the lines studied so as to avoid the influence of the grain of the photographic plates. The result obtained differed notably from that of

[1] Translated from advance proof sheets from *Journal de physique*, sent by the author.

[2] Runge and Paschen, *Astrophysical Journal*, **15**, 235, 1902; **15**, 333, 1902; **16**, 123, 1902.

[3] *Journal de physique* (4), **6**, 429, 1907.

Färber: we have explained the variation, which is more than 3 per cent, by examining critically the method adopted by Färber for measuring the fields; the bismuth spiral, which he used as intermediary, gives a quickly determined rough value of the field, but would require, in order to obtain precise results, precautions that are not taken.

The result of our measures was as follows: Let us call $\delta(\lambda)$ the difference between the outer components of these lines separated by the field, for example, the difference between the outer components of the pure triplet given by the line 4680; we have, using the electromagnetic C.G.S. units, that is, expressing λ and $\delta(\lambda)$ in centimeters and H in gausses:

$$\frac{\delta(\lambda)}{H\lambda^2}=1.875\times10^{-4}$$

in place of 1.813 given by Färber.

Our result was completely confirmed by the absolute measurements made at Tübingen by Mlle. A. Stettenheimer and by Gmelin.[1] The latter, who also measured the magnetic fields by two distinct methods, gives finally the value:

$$\frac{\delta(\lambda)}{H\lambda^2}=1.878\times10^{-4},$$

which differs from ours by only about two thousandths.

On the other hand, we may add that the following fact brings equally well an indirect confirmation to these measurements. When we published our work we assumed with Runge that the pure triplet of the line 4680 had double the separation of the normal triplet predicted by Lorentz' elementary theory. Our measurements on the blue lines of zinc led, however, on this assumption, to a value of the ratio e/m of the charge to the mass of an electron, smaller by 6 per cent than the value then accepted. From the preceding figures we may in fact deduce:

Weiss and Cotton.......... $\dfrac{e}{m}=1.767\times10^7$

Gmelin.................. $\dfrac{e}{m}=1.771\times10^7$

[1] *Annalen der Physik*, **28**, 1079, 1909.

But subsequently the direct measurements of the value of e/m for cathode corpuscles of small velocities have shown that it was the value deduced from the Zeeman phenomenon that was correct.[1] Here are the results of recent measurements:

Classen[2] . . . . $\frac{e}{m}=1.773\times10^7$

Bücherer-Kurt Wolz[3] . . . . $\frac{e}{m}=1.767\times10^7$

Malassez[4] . . . . $\frac{e}{m}=1.77\times10^7$

Bestelmeyer[5] . . . . $\frac{e}{m}=1.75\times10^7$

Today, then, we know more accurately the fields used by Runge and Paschen; in their research on the mercury spectrum; the field (the provisional value of which was 23,850) was in reality very near 23,000 gausses:

Weiss and Cotton	23,060
Gmelin	23,010

The other field (the value of which was assigned as 31,000), to which are referred the results derived by the same authors for the spark spectra, ought to be reduced in the same proportion, which would bring it down to about 29,900 gausses:

Weiss and Cotton	29,975
Gmelin	29,910

When the results given by Miller, Jack, etc., are compared with measurements where the magnetic field was determined directly, it is necessary, then, to remember that the numbers given refer to a field of 23,000 gausses and not of 23,850. For the same reason the results given by B. E. Moore[6] refer to a field of 23,600 gausses and not to a field of 24,450. Moore himself had taken care to

[1] Weiss et Cotton, *Comptes Rendus*, **147**, 968, 1908.

[2] *Physikalische Zeitschrift*, **9**, 768, 1908.

[3] *Annalen der Physik*, **30**, 288, 1909.

[4] *Annales de Chimie et de Physique*, **23**, 424, 1911.

[5] *Physikalische Zeitschrift*, **12**, 974, 1911.

[6] *Astrophysical Journal*, **28**, 8, 1908; **30**, 143, 1909; **32**, 385, 1911.

point out that later absolute measurements would make it possible to increase the precision of the value.

If we make this correction for Miller's results, which Purvis cites, we find that they approach those found by Babcock. But this correction only accentuates the difference between the results of Purvis and those of Miller. I had already noticed this difference, and called attention to the fact that the measurements of Purvis, which are fully stated elsewhere[1] and are very interesting, were not directly utilizable excepting as relative values, because the value of the magnetic field adopted (39,980) is certainly much too high. As Purvis, in his note, states that he has no doubt of the absolute value of this field, without giving the details of the method which he used to measure it, I will point out the way in which it can be calculated indirectly, starting from different measurements made by Purvis on his plates.

1. In his work on the lines of the elements *Pb*, *Sn*, *Sb*, *Bi*, and *Au*, Purvis has had occasion to measure the magnetic separations of the two lines λ 3383 of silver and λ 3274 of copper which behave like the D_1 line of sodium. Comparing the distance of the four components of these quadruplets with those found by Runge and Paschen, I obtain for the value of the field 30,800 instead of 39,980.

2. In his work on the lines of the elements *Ti*, *Cr*, and *Mn*, Purvis has measured the pure triplet given by the line λ 4274.9. This triplet is given by Miller as having double the normal separations; Dufour (unpublished measurement) working independently has verified this result.[2] Assuming this, I calculate for Purvis' field 29,800.

3. In the same work Purvis gives the results of several measurements on the lines of zinc, magnesium, and cadmium (second subordinate series). Purvis does not state expressly that the current was regulated to the same value as in the rest of the work. Assuming that it was, I find 29,600 approximately, using the absolute measurements previously stated for these lines.

[1] *Cambridge Transactions*, **20**, 193, 1906; *Proceedings Cambridge*, **13**, 82, 325, 354, 1906; *Proceedings Cambridge*, **14**, 43, 217, 1907.

[2] This line constitutes a part of a natural triplet of chromium which we find again in the ultra-violet. I wish to call attention here to the fact that the two other lines which inclose it do not give, as was supposed, pure triplets (Babcock, *Astrophysical Journal*, **33**, 382, 1911).

4. Finally, it is not only for the four lines of chromium cited by Purvis that the results vary considerably from those of Miller. For the other triplets of chromium and for the triplets of manganese, the same systematic disagreement is found. Comparing the values of the separations given for 20 triplets of these two substances, the ratio between the field used by Purvis and the one (23,000) to which Miller's results are referred, may be estimated. Thus I find again for Purvis' field 29,900: the relative values of the chromium lines alone would give only 28,500. Assuming this last value for the field, the results would agree with those of Miller and Babcock.

It is seen from this why, in the table of several measurements on the Zeeman effect that I prepared for the tables of the Société française de physique,[1] I stated that the results given by Purvis are obtained not with a field in the neighborhood of 40,000 but of about 30,000 only. Moreover, to obtain in the interspace used by Purvis (pole-pieces terminated by disks 7 mm in diameter, 4 mm apart) a field of 40,000, it would be necessary with the best iron obtainable to have a large instrument like the Weiss electromagnet, and Purvis would certainly have indicated the diameter of the cores in this case.

When we verify in this way systematic differences between the results obtained by two different observers, we are led to suspect that it is the measurement of the magnetic field that is its cause. Differences as great as in the case of Purvis are never found; but there are other examples where the differences in the values of $\frac{\delta(\lambda)}{H\lambda^2}$ reach 5 per cent or even 10 per cent. Thus the results of Hartmann on chromium are smaller than the others; it is quite probable that the direct measurement of the field (made by an induction method) explains here again the variations from the results of other physicists. In fact, the comparison of Hartmann's figures with those just obtained at the Zeeman laboratory, by Mme. I. M. Graftdijk on another spectrum, that of nickel, leads to the same conclusion: the magnetic fields given by Hartmann are a little too large.

[1] A. Cotton, *Le radium*, **8**, 42, 1911.

How may we avoid in the future similar difficulties in the comparisons—difficulties which take away part of their value from the results of measurements that require much time and patience? It would suffice to put greater care on the determination of the magnetic fields. This measurement can be made indirectly, utilizing the measurements on the zinc lines for which the absolute measurements have furnished results practically identical; it is this process that is actually employed at the Zeeman laboratory;[1] it is also the one that Stefan Rybar[2] employed in some recent work at Göttingen. This optical measure of the field is, besides, the best for studying the spark spectra obtained with electrodes of ferromagnetic metals, the presence of which necessarily affects the fields studied. Besides, it can be rather rapidly used, and the plates employed are suitable for precise measurements, if we are careful to render the lines very fine with a suitable self-induction connected in the discharge circuit (Hemsalech). The 4680 zinc line, which gives a pure triplet, is the best line to use.

It is not the only one that can be used; the measurements of Runge and Paschen, those we made at Zurich, and those made at Tübingen agree in showing that for other series lines the Zeeman effect varies proportionally to the field and can be used to measure it. But it is essential to reduce as much as possible the number of intermediary lines that serve finally to refer the measurement to the measurements properly called absolute. Each one of these comparisons introduces a slight uncertainty; should we, for example, use the simple relations established by Runge and Paschen, or take careful account of the very small variations from these simple laws which these physicists themselves find in the different measurements? From this point of view it would be desirable that the physicists who employ this process indicate with precision, in their articles, which lines they have used and what (in Ångström units, for example) are the variations actually measured on the plates used to study the field. In this manner we should later be able to render still more precise the results calculated for this field,

[1] Mme. Bild-Van Meurs, *Proceedings Amsterdam*, **11**, 223, 1908 (thèse d'Amsterdam); I. M. Graftdijk (thèse d'Amsterdam, December, 1911).

[2] *Physikalische Zeitschrift*, **12**, 889, 1911 (thèse de Budapest, 1911).

profiting by the more complete data that the succeeding researches will bring to the exact knowledge of the ratio between the magnetic separations of the different lines and the absolute values themselves.

The example of Purvis shows clearly that the direct measurement of the field can lead to errors when only one method has been employed to make this measurement in absolute value. A check is always necessary to avoid errors which can then escape even a very good physicist. An absolute measurement is, besides, fairly difficult, since one should verify or calibrate the apparatus which is used. The balance which in particular P. Weiss and I used, a further improved model of which P. Sève[1] described recently, gives rapidly, when we have a verified ammeter, a very precise value of the field, provided the interspace between the iron pieces is sufficiently wide. But we employ more often for the study of the Zeeman effect pole-pieces too small to allow the direct use of this instrument. It is then necessary to use the balance to calibrate, in a very uniform field, the combination of a small coil connected to a ballistic galvanometer or to a Grassot fluxmeter.[2] This last apparatus, once calibrated, is very convenient[3] and permits the frequent verification of the field which is being used. There is here a final precaution, necessary especially in researches extending over long periods of time, to which I think it useful to call attention. Usually the experimenter limits himself to measuring once for all the field for different values of the magnetizing current, and seeks afterward to restore the current to the same value in the magneto-optical measurements, properly so called. This process is theoretically legitimate, since for the strong inductions which are used, the errors coming from the "previous history" of the electromagnet are not appreciable. But it must not be forgotten that it

[1] *Comptes Rendus*, **150**, 1309, 1910. We shall find in Sève's paper, now in press, details on the use of this instrument, constructed by Pellin.

[2] Grassot, *Journal de physique*, **3**, 696, 1904 (apparatus constructed by the company for the manufacture of meters).

[3] Another method, suggested by Faraday, would also permit comparing a magnetic field, by a very rapid and sure method, with a standard field; we should use the properties of diamagnetic or paramagnetic crystals, measuring simply, for example, the periods of oscillation. I hope to come back in the future to this method which M. Sève and I have commenced to study.

is assumed that during the interval the ammeter has not been affected, this instrument does not contain magnets or springs that can be modified with time, and that it is also assumed that the coils of the electromagnet have remained well insulated.

An article by H. D. Babcock, which appeared in the December 1911 number of the *Astrophysical Journal* (**34**, 288), shows also that the preceding remarks are not without significance, and accentuates again the interest there would be in knowing better the absolute values of the separations measured in the different laboratories. Babcock was led by his own measurements on chromium and on vanadium,[1] and by the measurements of King[2] on titanium and on iron, made also at the Pasadena laboratory, to remark that the pure triplets of the non-series lines, which vary, as we know, between large limits, are not, however, distributed at random, but appear to group themselves about certain favored values.

Babcock did not know that I had myself called attention to this fact, and presented curves representing the distribution of the displacements according to their own size.[3] He finds again results analogous to mine, but our results are not identical, because Babcock used, without correcting them, the values of the magnetic field given in the papers of Miller and of Moore. Hence the agreement, which he points out between the mean value of the separations near the principal maximum and the value of the normal separation, appears to me altogether accidental. It would in reality be necessary for 8 of the 13 spectra studied to increase by 3 per cent the values of all the separations referred to the unit field.

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[1] *Contributions from the Mount Wilson Solar Observatory* Nos. 52 and 55; *Astrophysical Journal*, **33**, 217, and **34**, 209, 1911. The field is measured by a bismuth spiral.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 56; *Astrophysical Journal*, **34**, 225, 1911.

[3] Société française de physique, séance du 7 mai, 1909, *Bulletin des séances*, fasc. 4, p. 55, 1909. Reductions of two of these curves will be found in *Le radium*, **8**, 42, 1911. Mme. Graftdijk has just published a more complete study, from this point of view, of the iron spectra (138 triplets), and has published also similar curves for nickel (163 triplets) and for cobalt (59 triplets). Mme. Graftdijk finds also that the first maximum occurs for values exceeding notably the value for the normal state. She finds also for iron, but not for nickel, a maximum for a separation in the neighborhood of 3/2 of that of the normal state.

STANDARD WAVE-LENGTHS IN THE ARC SPECTRUM OF IRON, REDUCED TO THE INTERNATIONAL UNIT

I. FROM λ 4282 TO λ 5324

By F. GOOS

According to the plan of the International Solar Union[1] the secondary[2] international standards in the arc spectrum of iron are to be supplemented by tertiary standards, from 5 to 10 Ångström units apart, obtained from interpolation by means of a grating. To obtain the highest possible accuracy this work should, of course, be done only with the largest and best concave gratings; and yet in view of the fact that many observers and different methods are needed, I decided to take up the problem with a comparatively small plane grating.

1. THE PHOTOGRAPHIC APPARATUS

Through the courtesy of Professor Ames, to whom I take this opportunity of expressing my sincere thanks, I obtained a very beautiful two-inch plane Rowland grating, ruled with 7000 lines to the inch. The grating was mounted in the autocollimating fashion devised by Littrow, and in the fifth and sixth orders gave good, bright images. The objective, by Hilger, consists of two elements cemented together and achromatized in such a way as to give a color-curve which is practically a straight line from λ 4200 to λ 8000; the focal length increases from 194 cm in the violet to 197 cm in the red. The radii of curvature of the front and back surfaces of the lens were so chosen that the images of the slit reflected from these surfaces were real and were located about midway between slit and objective.

This renders it possible by a slight inclination of the objective to elevate one image and depress the other so that their glare no longer strikes the photographic plate, which is covered except for a narrow band on the side toward the objective. With this lens

[1] *Astrophysical Journal*, **32**, 259–260, 1910.

[2] *Ibid.*, **32**, 215–216, 1910; **33**, 85, 1911.

the dispersion is such that in the sixth order 1 Ångström is represented by 0.36 mm.

The slit lies 12 cm above the middle of the plate-holder; the supports for the slit, plate-holder, objective, and grating are made of mahogany and rest upon two strong brass rings. The whole apparatus is inclosed in a long, slender, light-tight wooden case so that for half an hour at a time the inside temperature can be held constant to within half a degree.

The electrodes are ordinary iron rods from 8 to 9 mm in diameter, carrying a current of 6 or 7 amperes, sometimes on the 110-volt circuit, sometimes on the 220-volt circuit. A "condensing lens" of 19 cm focal length is used in such a way that only the middle part of the arc is used, and so that the grating is illuminated with perfect uniformity.

2. THE PHOTOGRAPHS

The spectra of the sixth order were employed for the photographs, thus requiring the use of two light-filters, one to cut out the higher orders and one the lower orders. For this purpose the gelatin sheets of Wratten & Wainright served admirably. In the blue and violet, the ordinary fast plate of different makes was employed; but for the longer wave-lengths the panchromatic plates of the firm above named. In the region of λ 4200 the exposure was about half a minute; at λ 4500, one minute; at λ 4800, two minutes; at λ 5100, three and a half minutes; at λ 5400, five minutes. Throughout the entire work, the width of the slit was $\frac{1}{50}$ of a millimeter; the inclination of the plate toward the normal varied from 5 to 8 degrees.

One of the sixth-order spectra, the one employed for the earlier photographs, gave good images with a fine sharp line in the middle upon which one could set the reading microscope very accurately. The limit of resolution in the violet was 0.10 Å. The available field amounted to approximately 7 cm or 200 Å. I soon, however, came to prefer the other spectrum of the sixth order, which gave lines a little wider, but of perfectly uniform density; the resolving power was a little smaller, only 0.13 Å., in the violet; the field was here a little larger, about 10 cm, that is, 280 Å.; so that in general from ten to eleven of the secondary iron standards were found upon

a plate, a matter of the highest importance in the evaluation of standards.

The striking difference between the slit-images of the right and left sixth order, which is also observed between the right and left of lower orders, probably finds its explanation in some asymmetry in the groove on the grating. Since each region of the spectrum is photographed some seven or eight times, the plates are so set that the wave-length in the middle of each plate is advanced by 35 Å. In this manner every line appears in from seven to eight different places on different plates, and each secondary standard is gradually displaced from one end, through the middle, to the other end of the plate; so that in the computation of the wave-lengths a little later, a smoother result is obtained.

For the determination of wave-lengths between λ 4282 and λ 5324 thirty-seven plates were taken, covering the following ranges:

No. of Plate	From λ	To λ	No. of Plate	From λ	To λ
1	4148	4353	20	4737	5002
2	4148	4376	21	4754	5012
3	4191	4376	22	4790	5050
4	4191	4427	23	4824	5083
5	4234	4467	24	4860	5127
6	4282	4467	25	4903	5167
7	4282	4531	26	4919	5192
8	4315	4495	27	4966	5233
9	4353	4531	28	5002	5267
10	4427	4593	29	5050	5302
11	4427	4647	30	5083	5324
12	4467	4707	31	5110	5371
13	4467	4737	32	5167	5406
14	4531	4790	33	5167	5435
15	4548	4790	34	5192	5456
16	4593	4860	35	5233	5498
17	4603	4878	36	5267	5507
18	4647	4919	37	5302	5570
19	4691	4966			

3. THE MEASUREMENTS AND THE DETERMINATION OF WAVE-LENGTHS

The measurements were made by means of a Töpfer micrometer, the screw of which had a pitch[1] of one-half mm. In place of the ordinary eyepiece I used the Zeiss binocular designed by Abbé. By the addition of an auxiliary objective this was transformed into

[1] F. Goos, *Zeitschrift für Instrumentenkunde*, **31**, 52, 1911.

a regular binocular microscope, with which one can directly observe the image of the spectral line in the focal plane of the ordinary objective. The image produced by the complete system is erect. The use of both eyes not only enables one to set on the line with much greater ease, but also prevents weariness of the eyes even after a long series of measures. Each line is measured eight times on each plate, four times in position "I"—longer wave-lengths to the right—and four times in position "II"—longer wave-lengths to the left. In each of these positions two settings are made with a right-handed rotation of the screw, and two with a left-handed rotation.

As a dispersion formula I have used

$$\lambda = a + bx + cx^2$$

where λ is the wave-length; x, the reading of the screw; and a, b, c, are constants. (1 rev. = 0.5 mm.)

The constants for each plate were determined from three secondary standards, one at the left end, one in the middle, and one at the right end.

In general, $b = +1.4$; $c = -0.0001$.

But this simple formula does not perfectly represent the other secondary standards on the plate. These outstanding differences were corrected graphically by means of a correction-curve. In the earlier plates (sixth order on the right) there were some seven or eight of these standards; in the case of the other plates (sixth order on the left) as many as ten or eleven of the standards were shown on a single plate; so that these curves could be drawn with great accuracy and the standards adjusted among themselves. These correction-curves have somewhat the form of a sine curve with an amplitude of about 0.02 Å.

4. RESULTS

The following table contains the wave-lengths of 184 lines, derived from 1292 single measures. Each line has in general been measured seven times. As mentioned above, the measurements are distributed over thirty-seven plates. Certain weak lines were missing on some of the plates; but no line is given in the table which has not been measured at least three times. The third

λ	Intensity	No. of Plates	Mean Error	I. A.	λ−I. A.	D_s	D_g	Remarks
4282.408	5	7	±0.001	.408	0.000	+0.004	0.000	Kayser gives the intensity as 4
94.130	6	7	2			+ 3	+ 3	
99.247	6	7	1			+ 3	+ 1	
4307.912	8	6	4			+ 2		
15.089	5	8	1	.089	0	0	− 1	
25.764	8 *R*	8	5			0	+ 1	
37.052	4	8	2			+ 1	− 2	
52.741	4	9	1	.741	0	+ 3	− 2	
58.510	2	6	3			+ 4	+ 6	
67.584	3	8	2			+ 5		
67.905	2	8	2			+ 5		
69.778	3	8	1			+ 6	+ 6	
75.934	4	8	1	.934	0	+ 6	− 2	
83.551	10 *R*	6	4			+ 6	− 7	
88.420	3	6	1			+ 6		
90.956	2	5	3			+ 6	0	
4404.755	8 *R*	6	2			+ 5	− 3	
07.716	3	6	1			+ 5		
08.420	3	6	1			+ 5		
15.129	7	6	2			+ 5	− 1	
22.574	3	6	1			+ 5	+ 7	
27.314	4	8	1	.314	0	+ 5	− 5	
30.623	3	7	3			+ 5	0	
33.215	2 *u*	6	3			+ 5		
42.349	4	7	1			+ 5	+ 1	
43.197	3	7	2			+ 5		
47.725	4	7	2			+ 5	− 3	
54.384	3	7	2			+ 5	− 3	
59.127	4	7	2			+ 5	+ 2	
61.660	4	7	1			+ 5	+ 3	
66.555	4	9	1	.556	− 1	+ 5	− 3	
69.396	3 *u*	7	2			+ 5	+ 9	
76.024	4 *ur*	6	1			+ 5		
82.173	3	5	3			+ 5	+ 5	
82.270	4	5	5			+ 5	− 1	
84.241	3	7	2			+ 5		
89.747	2	7	2			+ 5	− 2	
90.085	2	6	3			+ 5	− 8	
94.573	4	7	1	.572	+ 1	+ 4	− 2	
4514.196	1	4	4			+ 2	+ 2	
17.543	1	4	3			+ 2	+ 2	
25.155	3	6	3			0	+ 3	
28.622	5	6	1			− 1	+ 1	Eversheim's interferometer value is 4528.622
31.154	3	7	1	.155	− 1	− 1	− 4	
47.854	3	6	1	.853	+ 1	− 2	− 3	
52.552	1	6	3			− 2		
56.125	3 *u*	6	3			− 1	− 1	
74.732	1	6	3			+ 2	+ 1	
81.541	2	6	4			+ 3	+ 11	
87.138	1	6	2			+ 4	− 1	
92.660	3	7	1	.658	+ 2	+ 5	− 1	
98.144	2	6	1			+ 6	+ 2	
4602.017	1	6	1			+ 6	+ 7	
02.945	4	7	1	.947	− 2	+ 6	− 6	
11.298	3	6	2			+ 7	− 4	

λ	Intensity	No. of Plates	Mean Error	I. A.	λ−I. A.	D_s	D_z	Remarks
4613.236	2	5	±0.003		0.000	+0.007	+0.004	
19.300	3	6	3			+ 8	− 3	
25.073	3	6	2			+ 8	− 1	
32.915	3	6	2			+ 8	− 10	
37.528	3	6	2			+ 8	+ 3	
38.026	3	6	1			+ 8	− 1	
47.439	4	7	1	.439		+ 8	− 5	
54.514	3	6	2			+ 8	+ 11	
54.645	3	6	4			+ 8	− 2	
67.457	4	7	2			+ 5	− 5	
68.157	4	7	3			+ 5	+ 4	
73.178	3 *u*	7	6			+ 4	+ 7	
78.856	4	7	1	.855*	+ 1	+ 3	− 1	
83.575	1	7	3			+ 2	− 7	
91.414	3	8	1	.417	− 3	+ 1	− 2	
4707.289	4	8	1	.288	+ 1	− 2	+ 2	
10.281	3	7	2			− 2	+ 3	
21.000	1	4	5			− 3	+ 4	
27.425	2 *u*	7	2			− 4	− 9	*Fe, Mn*
33.587	2	7	2			− 4	− 1	
36.789	4	8	1	.786	+ 3	− 4	+ 6	
41.529	2	7	2			− 4	+ 3	
45.792	2 *u*	7	3			− 4	− 6	
54.046	3	8	2	.047*	− 1	− 3	0	*Mn*
57.572	1	6	3			− 3	− 1	
62.372	3	8	2			− 3	+ 4	*Mn*
65.861	2	6	3			− 2		*Mn*
66.420	2	7	2			− 2	0	*Mn*
72.812	2	8	2			− 2	− 2	
83.437	3	8	2			− 1	+ 2	*Mn*
86.810	2	8	2			− 1	0	
89.654	3	9	1	.657	− 3	− 1	+ 4	
98.273	1	3	2			0	− 5	
4800.648	1	7	4			0	− 5	
02.885	1	7	2			0	− 1	
07.734	1	3	4			0	− 1	
23.526	4	8	1	.522*	+ 4	0	+ 3	*Mn*
32.734	1	4	7			0	0	
39.546	1	8	3			0	0	
43.161	1 *u*	7	5			0	0	
55.690	1	4	2			− 1	− 2	
59.756	4	9	1	.758	− 2	− 1	+ 3	
63.665	1	5	6			− 2	+ 3	
71.329	5	8	2			− 2	− 2	
72.155	4	8	1			− 2	+ 2	
78.226	4	8	1	.225	+ 1	− 2	− 1	
81.718	1	6	4			− 2	− 4	
82.160	1	6	3			− 2	− 4	
85.441	2 *u*	6	3			− 2	− 2	
90.769	5	7	1			− 2	0	
91.510	6	7	1			− 2	+ 2	
4903.325	4	8	1	.325	0	− 2	+ 4	
10.035	1	7	4			− 2	+ 6	
19.006	5	9	1	.007	− 1	− 2	− 6	
20.518	7	8	1			− 2	− 3	

λ	Intensity	No. of Plates	Mean Error	I. A.	λ−I. A.	D_s	D_z	Remarks
4924.768	2	8	±0.002		0.000	−0.002	−0.007	
38.196	1	7	4			−2	+3	
38.827	3 *u*	8	2			−2	−1	
39.679	2	8	1			−2		
40.406	2	8	3			−2	0	
57.306	4	6	3			−2	+5	
57.613	5	6	2			−2	+6	
66.105	3	9	1	.104	+1	−2	+2	
73.114	2	7	2			−2		
78.619	1 *ur*	6	6			−2	+1	
82.541	3 *u*	8	3			−2	+14	
85.269	2	8	3			−2	−3	
85.564	2	8	3			−2	−3	
94.131	2	8	3			−2	−6	
5001.882	3	9	1	.881	+1	−2	0	
05.732	3	8	2			−2	+2	
06.137	4	8	2			−2	+3	
12.070	3	8	1	.073	−3	−2	+2	
14.961	2	7	1			−2	+4	
22.249	2	7	1			−3	−6	
28.126	1	7	3			−3	−7	
41.072	2	7	2			−4	−3	
41.758	3	7	2			−4	+4	
49.828	3	8	1	.827	+1	−4	+7	
51.640	3	7	1			−4	+4	
68.786	3	7	2			−4	+4	
74.722	3 *u*	7	2			−4	−14	
79.226	3	7	2			−4	−1	
79.741	2	7	1			−4	−6	
83.346	2	8	1	.344	+2	−4	+4	
96.999	1	5	4			−3	+2	
98.696	3	7	2			−2		
5105.547	2	7	3			−1		*Cu.* Interferometer value of Fabry-Buisson 5105.543
07.468	2	6	2			−1	+7	
07.643	2	6	2			−1	−6	
10.411	3	8	1	.415	−4	0	−1	
23.732	2	8	2			+2	+1	
27.367	2	8	1	.364*	+3	+2	−1	
(33.646)	3 *u*	7	3			+3	−(32)	Kayser gives the intensity as 1
39.278	3	6	3			+3	+7	
39.493	4	6	3			+3	+8	
42.934	2	7	3			+4	−4	
50.847	2	7	3			+4	+2	
51.916	2	6	3			+4	−3	
(62.347)	3 *ur*	7	3			+4	+(33)	
67.490	5	9	2	.492	−2	+4	−2	
71.602	4	8	2			+4		
91.469	4	8	1			+4	−12	Eversheim by the interferometer obtains 5191.473
92.364	4	9	1	.363	+1	+4	−2	
94.951	3	8	2			+4	+1	
98.720	1	8	2			+4	−1	
5202.341	2	8	3			+4	−4	
08.614	2	7	3			+3	−8	
15.197	2	8	2			+3	+1	
16.279	3	8	2			+3	+1	

λ	Intensity	No. of Plates	Mean Error	I. A.	λ−I. A.	D_s	D_z	Remarks
5217.409	2	8	±0.002		+0.000	+0.003	+0.003	
26.873	3	8	2			+ 2	− 3	
27.194	4	8	2			+ 2	+ 7	
29.862	2	8	2			+ 2	+ 17	
32.955	5	9	1	.957	− 2	+ 2	− 7	
35.382	1	8	2			+ 1		
42.495	1	8	2			+ 1	− 1	
50.644	1	8	3			0		
63.318	2	8	2			− 1	0	
66.570	4	9	1	.569	+ 1	− 1	− 3	
69.532	6	8	1			− 1	− 2	
70.353	5	8	1			− 1	0	
73.178	2	8	3			− 1	+ 3	
73.371	1	5	4			− 1	− 6	
81.808	3	8	1			− 1	+ 3	
83.635	3	8	1			− 1	+ 1	
5302.316	2	9	1	.315	+ 1	0	+ 2	
07.364	1	7	3			+ 1	− 1	
24.195	4	8	1	.196	− 1	+ 2	− 4	

column gives the number of plates upon which the line has been measured. Column 2 gives the intensities. These adhere as nearly as possible to Kayser's[1] system and were estimated either with the naked eye or with a low-power eyepiece; they indicate, therefore, mainly the visibility of the line without regard to its breadth or blackness. The intensity of the weakest lines is denoted by 1; that of the strongest, by 10.

In general the numerical values agree well with those of Kayser; only in the case of the lines λ 4294 and λ 5134 is there a deviation as great as two units. Lines which are not sharp are so marked in this column, where the following nomenclature is employed:

u = hazy;
ur = hazy toward the red;
uv = hazy toward the violet.

R denotes that the line is easily reversed. Column 4 gives the "mean error" of the wave-lengths computed by taking the average value from the different plates, giving equal weight to all the measures.

Taking the average for the entire series, this mean error, ϵ amounts to ± 0.0022 Å.; hence the "probable error," r, is

[1] H. Kayser, *Astrophysical Journal*, **32**, 217, 1910; *Zeitschrift für wissenschaftliche Photographie*, **9**, 173, 1911.

±0.0015 Å. A mean error of ±0.005 occurs four times; one of ±0.006 occurs three times; one of ±0.007 occurs once; these have to do mostly with lines which are not sharp or with lines which were measured only four or five times.

Besides the iron lines are included some which appear as impurities; among these are seven manganese lines and one of copper.

Column 5 gives the values of the thirty-six secondary standards from which the other wave-lengths are determined by interpolation. Besides the standards established by international agreement, I have employed four others which rest upon the interferometer measurements of Fabry and Buisson,[1] and Eversheim;[2] these are indicated by asterisks.

The agreement with standards is excellent throughout. The deviations which are given in column 6 never exceed 0.004 Å., and reach this value only in two cases out of thirty-six. The sum of the positive deviations amounts to +0.025 Å.; that of the negative, to −0.026 Å.; so that the average deviation is $\frac{0.051}{36}=$ ±0.0014 Å. It is, therefore, perhaps fair to assume that the wave-lengths of these lines are accurate to 0.001 Å. It is, however, a rather striking fact that the larger deviations occur precisely in those lines for which the three interferometer measures, by which the secondary standards are determined, agree very well.

The probable error mentioned above, ±0.0015 Å., as an average for the entire series, naturally gives no information except regarding the accuracy of wave-lengths determined by my particular instrument. Whether my measures are actually correct to within the limits assigned can be answered only by comparison with measures obtained on other apparatus. The only results yet available for purposes of such a comparison are those of Kayser. His values show striking systematic differences with respect to mine, differences which need explanation. By means of some of his spectrograms, which he has kindly placed at my disposal, I think I have found[3] that these deviations are to be explained by the fact that

[1] *Trans. International Union for Solar Research*, **2**, 138, 1908.

[2] *Annalen der Physik* (4), **30**, 815, 1909.

[3] *Zeitschrift für wissenschaftliche Photographie*, **10**, 200, 1911.

Kayser has used a simple linear interpolation between each two of the secondary standards and then averaged the results. The larger deviations which thus occur between individual values point, in Kayser's opinion, to irregularities in the system of secondary standards.

But I have found the improved (smoothed-out) values of the secondary normals given by Kayser to be only partially confirmed.

In order to compare Kayser's wave-lengths with mine, it is first necessary to place in evidence the systematic deviations. Column 7, headed "D_s," gives these differences, in the sense of Goos-Kayser, determined graphically. We observe that the variations at λ 4630 reach the value $+0.008$ Å., while the deviations on the negative side are not so considerable and at λ 4740 and λ 5060 are only -0.04 Å.

I have neglected those small differences—amounting at most to 0.002 Å.—which result from the fact that Kayser has used standards whose values depend not only upon the measurements of Fabry-Buisson and Eversheim but also upon those given by Pfund[1] in 1908, reduced, however, to the value 6438.4696 for the red cadmium line, while the international secondary standards established later depend upon Pfund's[2] more recent work.

Column 8, headed "D_z," contains the accidental differences which remain after correcting for the systematic differences.

Kayser and I have observed in common 163 lines. The sum of the positive deviations amounts to $+0.284$ Å., the negative to -0.285 Å. The average deviation is therefore $\frac{\pm 0.569}{163} = \pm 0.0035$ Å.

Computed from the above the probable error of a single observed difference between my measures and those of Kayser is approximately $\pm 0.0035 \times 0.845 = \pm 0.0030$ Å.; giving equal weight to each observer, the probable error of a single wave-length determination for each observer becomes ± 0.0021 Å. This value is larger than that computed above from the internal agreement of my own measurements, namely, ± 0.0015 Å.

[1] *Astrophysical Journal*, **28**, 197, 1908.

[2] *Ibid.*, **32**, 215, 1910.

It is evident also that if the weight is properly distributed, there are still other sources of error to be looked for in the method itself; perhaps one's estimation of the center of gravity of a line is different in the case of a spectrogram such as that of Kayser, which has a dispersion three or four times as great as mine.

In fourteen cases the accidental deviation is greater than 0.008 Å. Concerning these the following is to be noted:

The lines λ	4469.4	deviation	+0.009	are marked as hazy
	4727.4	"	−0.009	
	4982.5	"	+0.014	
	5074.7	"	−0.014	
The lines λ	4490.1	"	−0.008	are components of close doubles
	4654.5	"	+0.011	
	5139.5	"	+0.008	
The lines λ	4581.5	"	+0.011	are sharp lines in which the deviation is not immediately explicable
	4632.9	"	−0.010	
	5191.5	"	−0.012	
	5208.6	"	−0.008	
	5229.9	"	+0.017	

In the case of the line λ 4581 the mean error is rather great— +0.004; the line λ 5191, given by Eversheim's interferometer measurement as 5191.0473, shows also a deviation of −0.004 Å. from my measurements. The line 5229.9 was measured by me eight times, with a mean error of +0.002, the individual measures being

	5229.852
	858
	861
	860
	868
	870
	862
	865
Mean	.862

The difference between this and Kayser's value of 5229.845, after a correction for systematic differences, is very striking. The

lines 5133.6, with a deviation of −0.032 Å., and 5162.3, with a deviation of +0.033, must be at once thrown out. They are both very hazy. I have placed them in brackets in the table and have omitted them from consideration in deriving the probable error. They are not at all available for the purpose of standards.

The measurement of close doubles naturally offers some difficulty and it is apparent that my distances turned out to be smaller than those of Kayser. In the following table are collected under the headings "G" and "K" the distances of all doubles less than 0.410 Å.

Double	G.	K.	G.−K.
	Å.	Å.	Å.
5005.7–6.1	0.405	0.404	+0.001
4489.7–90.1	0.338	0.344	−0.006
5226.9–7.2	0.313	0.311	+0.002
4957.3–7.6	0.307	0.306	+0.001
4985.3–5.6	0.295	0.295	0.000
5139.3–9.5	0.215	0.214	+0.001
5273.2–3.4	0.193	0.202	−0.009
5107.5–6	0.175	0.188	−0.013
4654.5–4.6	0.131	0.144	−0.013
4482.2–2.3	0.097	0.103	−0.006

It is to be hoped that these doubtful cases may soon be cleared up by measurements in the iron spectrum made by other observers. I am expecting soon to extend these measurements toward the red as far as to λ 6495.

HAMBURG, PHYSIKALISCHES STAATSLABORATORIUM
December 20, 1911

PRELIMINARY STATEMENT OF THE EARLY OBSERVATIONS OF *NOVA GEMINORUM* NO. 2, MADE AT THE OBSERVATORY OF THE UNIVERSITY OF MICHIGAN

By R. H. CURTISS

A brief résumé of the results obtained prior to March 23 by observation of *Nova Geminorum* No. 2 at the University of Michigan is contained in the following statement.

All estimates of magnitude were obtained by comparison with neighboring stars, according to Argelander's method. The spectra were made with a single-prism spectrograph, and with one exception in the photographic region.

March 13. At 11^h Central Standard Time, Mag. = 3.9.
Exposures: $9^h\ 4^m$ C.S.T. on Seed 23.
$9^h\ 27^m$ C.S.T. on Seed Lantern Slide.
$10^h\ 2^m$ C.S.T. on Seed Lantern Slide.
$11^h\ 0^m$ C.S.T. on Seed 23.
$11^h\ 40^m$ C.S.T. on Seed 23.

On all these plates the continuous spectrum resembles that of *Altair*, with alternating wide regions of emission and absorption. The comparison with *Altair* extends only to the character of the spectrum, however, and not to the position of the lines. Few narrow dark lines are to be found in the spectrum. Nearly all the prominent lines of Type F 5 are faint or absent. No certain trace of such strong F 5 lines as λ 4481 and λ 4549 can be found in the *Nova*, but the strong blend at λ 4172 seems to be represented. There is also strong absorption in the *Nova* in the neighborhood of the G band, possibly partly due to titanium. Probably other identifications with lines of type F 5 might be made, but such lines are difficult and apparently not numerous. On the other hand there are absorption lines in the *Nova*, not certainly associated with the bright lines, which are weak or absent in *Procyon*.

The lines $H\delta$, $H\gamma$, $H\beta$, λ 5016, λ 4922, and λ 4472 of helium, H and K of calcium, are all strong lines with complex structure. A heavy broad absorption component (in λ 4922 clearly double, in

$H\delta$ multiple) is strongly displaced toward the violet. Wide emission is clearly present on the red edge of these lines and in case of the calcium lines, sharp dark reversals, and in the hydrogen and helium lines probably weak dark reversals, all indicating a small velocity of recession, are present in this emission. Emission is present also on the violet edge of the absorption components of some of these lines, but is weaker and less extensive than that on the edge of greater wave-length.

The displacement of the absorption groups of the principal lines for this date follows.

Lines:	*Ca:* K,	H;	*He:* λ4471,	λ4922,	λ5016;	*H:* $H\delta$,	$H\gamma$,	$H\beta$
Disp. in Å:	−7.80,	−7.70,	−8.60,	−4.50,	−3.50,	−5.80,	−6.50,	−8.15.

This displacement increases with the square of the wave-length for the hydrogen lines, differs for different elements, and is quite different for helium and the so-called parhelium.

The sharp reversals of the calcium lines indicate a velocity of +5 km ± 3 km.

March 15. At 6^h C.S.T. Mag. = 4.2; 12^h, Mag. = 4.9.
Exposures: 10^h 0^m C.S.T. on Seed 23.
11^h 45^m C.S.T. on Seed 23.

The continuous spectrum is similar to that of March 13, but with contrasts much increased. λ 4481 is now visible as a diffuse line, but λ 4549 of *Ti–Fe* cannot be certainly seen. λ 4172 is strong and accompanied by emission. Well-marked absorption lines have developed at λ 4363, λ 4611, λ 4670. In the case of the complex lines, K, H, and $H\epsilon$, $H\delta$, $H\gamma$, λ 4472, $H\beta$, λ 4922, and λ 5016, the absorption lines have about the same intensity as on the previous plates, but are displaced about one Ångström farther toward the violet. The emission on the edge of greater wave-length has increased greatly, and shows a strong maximum near the normal position of the line with evidences of reversal. The velocity from the H and K reversals is +10 kilometers.

March 16. At 9^h C.S.T., Mag. less than 5.5.

Unsuccessful exposure through heavy sky shows only bright lines.

March 17. At 9^h C.S.T. Mag. = 5.7.
Exposures: 9^h 25^m Seed 30.
11^h 15^m Seed 30.

No marked changes in the continuous spectrum are shown, but a less marked alternation of bright and dark maxima is seen. Bright lines are relatively much stronger, with the strong displaced absorption lines of hydrogen and helium much weaker or absent. The position of the edge of the strong emission lines toward the red remains unchanged, while the edge toward the violet has extended greatly (ten Ångströms in the case of $H\beta$) covering the dark lines of two nights before. A strong emission maximum has appeared near the red edge of all hydrogen and helium emission lines mentioned above, with the possible exception of λ 4472. Other regions uncertainly bright on the plates of March 13 are now much stronger, as for example λ 4230, λ 4590, and λ 4610–4670. There is no emission which can certainly be traced to the lines of nebulum except possibly at λ 5007. The emission at λ 4472 is now very weak. Velocity from the H and K reversals = +9 kilometers.

March 18. At 8^h C.S.T. Mag. = 5.2.
Exposure: 8^h 27^m Seed 30.

Continuous spectrum shows little change. The emission lines are now slightly narrower than on the previous night, and with much sharper edges generally marked by absorption. Width of the $H\beta$ line about 35 Å. The violet edges of the emission lines have grown brighter, forming a companion emission maximum with the strong nucleus near the red edge of these lines. Velocity from H and K reversals = +6 kilometers.

March 19. At 10^h C.S.T. Mag. = 5.1.
Exposures: 10^h 0^m Seed 30.
11^h 18^m Seed 30.

Continuous spectrum little changed. There is now little resemblance to the spectrum of *Altair*. Several fairly well-defined narrow absorption lines are present. Strong emission lines are still contracting, with absorption at edges coming out more strongly. Two distinct emission maxima are clearly defined near either edge of the emission lines as on the previous night. There is no emission that can certainly be traced to the nebular lines λ4363, λ4686, and λ4960. Velocity from H and K reversals = +7 kilometers.

March 22. At 8^h C.S.T. Mag. $= 4.9$; at 11^h Mag. $= 4.7$.
Exposures: $8^h\ 48^m$ Seed 30.
$11^h\ 0^m$ Seed 23 bathed in Pinachrome.

On the slower (Seed 23) plate, alternate bright and dark maxima in the continuous spectrum are clearly shown and in many cases the maxima of emission of March 22 correspond to the maxima of absorption of March 13. The spectrum seems to have been reversed in a little more than a week. This finds explanation if it be assumed that complex lines resembling the strong lines of hydrogen and helium are distributed well over large regions of the spectrum.

The changes since March 19, in the strong lines of hydrogen and helium, are very marked. The strong emission band remains of the same width, bordered by well-defined absorption. On the edge toward the violet this absorption is widely double for the hydrogen and helium lines, the component of shorter wave-length being the stronger for $H\beta$, $H\gamma$, $H\delta$, and $H\zeta$, and the weaker for the helium lines. In the case of $H\gamma$, at least, emission extends faintly over the absorption lines on both edges of the strong bright line. The emission lines show the emission maxima near their edges noted previously, with several dark lines in the region between. In the region from $\lambda 5000$ to $\lambda 6600$, a number of complex bright lines are shown. The D lines have the same general structure as the H and K lines of calcium. A second strong absorption line on the side of shorter wave-lengths may be due to D_3 or may be a second component of the dark edge of the sodium emission. There is no certain indication of nebulum emission between $\lambda 3880$ and $\lambda 5020$.

Velocity from D_1, D_2, H, and K reversals $= +13$ kilometers.

ANN ARBOR, MICH.
March 23, 1912